A PARAMETRIC ANALYSIS OF A DEEP SEA RADIOISOTOPIC THERMOELECTRIC GENERATOR EMPLOYING A HEAT PIPE

by

Benjamin James Ewers

United States Naval Postgraduate School

THESIS

A PARAMETRIC ANALYSIS OF A DEEP SEA RADIOISOTOPIC THERMOELECTRIC GENERATOR EMPLOYING A HEAT PIPE

by

Benjamin James Ewers, Jr.

June 1969

A Parametric Analysis of a Deep Sea Radioisotopic

Thermoelectric Generator Employing a Heat Pipe

by

Benjamin James Ewers, Jr.
Lieutenant (junior grade), United States Navy
B.S. in Nuc.E., Rensselaer Polytechnic Institute, 1968

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1969

ABSTRACT

A parametric design analysis was performed using a heat pipe in an existing deep sea Radioisotopic Thermoelectric Generator (SNAP-21). Heat is transferred from an annular fuel pellet to an annular thermoelectric generator through a connecting heat pipe. The fuel pellet is fully shielded so that the thermoelectric generator is easily removable. Overall efficiency and the weight of major components were determined for varying fuel radii of from 1.3 inches to 1.7 inches and for varying insulation thicknesses of from 1.0 inch to 2.0 inch.

The analysis indicates that there is a particular fuel radius (at constant insulation thickness) at which minimum weight is reached, while the maximum overall efficiency is obtained at a larger fuel radius. The median design has an overall efficiency (at the beginning of life) of 5.4% and a total weight of 570 lbs. These design results, when compared to the existing SNAP-21 design gives an increase in overall efficiency of at least 7%, and a reduction in total weight of 12%.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

NOMENCLATURE

Symbol	
B	nuclear radiation buildup factor
D	dose rate due to nuclear radiation (mr/hr)
E	energy of nuclear radiation (ev)
k_c	thermal conductivity of the fuel capsule (BTU/hr-ft-°F)
k_f	thermal conductivity of the fuel (BTU/hr-ft-°F)
k_I	thermal conductivity of the insulation (BTU/hr-ft-°F)
k_s	thermal conductivity of the biological shield (BTU/hr-ft-°F)
LF	length of fuel (in)
P	source strength for volume source (Curies)
$\left(\frac{Q}{\ell}\right)_{in}$	heat transfer rate to heat pipe from fuel/unit length (BTU/hr-ft)
$\left(\frac{Q}{\ell}\right)_{out}$	heat transfer rate through insulation from fuel/unit length (BTU/hr-ft)
RF	outer radius of the fuel (in)
RI	outer radius of the insulation (in)
RS	outer radius of the shield (in)
t_c	self absorption thickness (in)
t_i	shield thickness (in)
T_H	hot end temperature of thermoelements (°F)
Z	distance from source to where dose due to nuclear radiation is to be measured (in)
η_c	Carnot efficiency (%)
η_m	material efficiency (%)
η_o	overall efficiency (%)
μ_i	attenuation coefficient of shields (1/in)
μ_c	attenuation coefficient of source (1/in)

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professors Paul J. Marto and Paul F. Pucci for their original thoughts that started this project and for their help and guidance throughout the course of the investigation. The author is also indebted to the 3-M Company for their cooperation in providing information on the SNAP-21 program.

I. INTRODUCTION

Future demands for measurements of oceanographic data needed to support scientific, commercial, and military operations necessitates the development of reliable power sources for deep sea use. For these undersea missions that require continuous, relatively low levels of electrical power for a few years, radioisotope powered systems are needed. Because isotope fueled themoelectric generators do not require oxygen and have no continuously discardable waste (i.e., no exhaust), the performance of these systems are independent of the environment in which they operate [14][1]. These advantages make them the ideal source of power for this application.

The 3-M Company has designed a radioisotopic thermoelectric generator (RTG) for just such a purpose (SNAP-21). The basic features of the SNAP-21 design are shown in figure 1, with the SNAP-21 system capabilities and parameters in table 1 [12]. SNAP-21 is constructed so that it is a fully shielded device with a removable generator, making the handling and maintenance easier. The RTG's predicted reliability and long life fulfills the requirements for deep sea use. The maximum temperature of the fuel in the SNAP-21 design is 1700°F (as listed in table 1) while the hot end temperatures of the thermoelements is 1000°F. This 700°F temperature drop from the fuel pellet to the themoelectric generator is due to heat conduction through the biological shield.

A heat pipe can be introduced to the SNAP-21 design to enhance the

[1]Numbers in brackets refer to bibliography

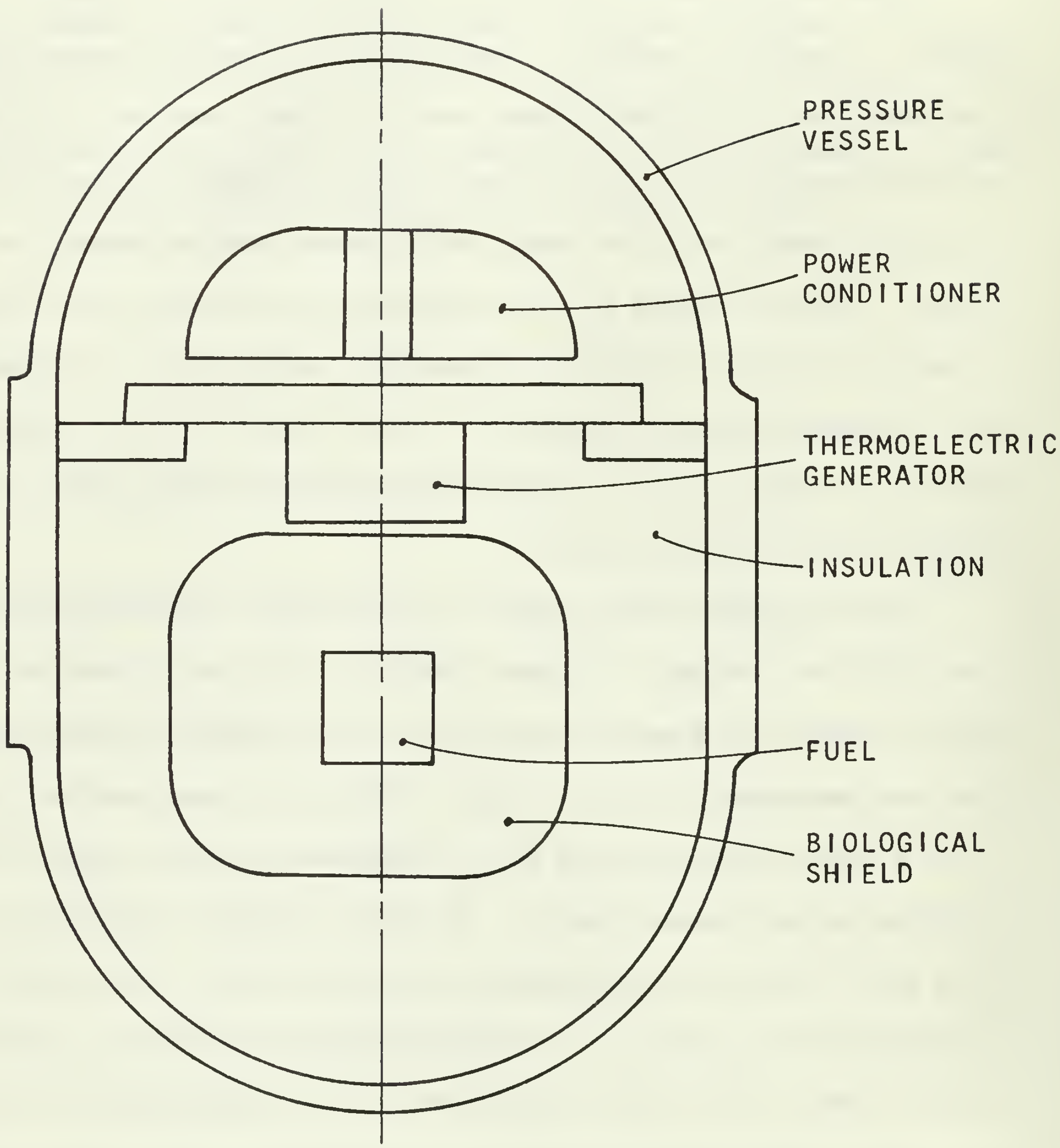


Figure 1
(Basic features of the SNAP-21 design)

POWER OUTPUT	10 watts
EXTERIOR SURFACE MATERIAL	Copper on Titanium
DESIGN LIFE	5 years
SYSTEM OUTPUT VOLTAGE	
with power conditioner	24 VDC
without power conditioner	4.7 VDC
LOAD CURRENT	
with power conditioner	.42 amp
without power conditioner	2.1 amp
NET SYSTEM EFFICIENCY	
end of life	6%
beginning of life	5%
GENERATOR EFFICIENCY	8-9%
POWER CONDITIONER EFFICIENCY	90%
FUEL TYPE	$SrTiO_3$
FUEL LOADING	33,000 curies
FUEL TEMPERATURE MAX	1700 °F
T/E HOT JUNCTION TEMP, MAX	1000 °F
T/E COLD JUNCTION TEMP, MAX	120 °F
OPERATION DEPTH, MAX	20,000 feet
WATER TEMPERATURE	28-41 °F
TOTAL WEIGHT	640 lbs

TABLE 1

(SNAP-21 System Parameters)

heat transfer from the heat generated in the fuel pellet to the hot plate of the generator. The heat pipe consists of essentially a closed evacuated pipe whose inside walls are lined with a capillary structure (called a wick) saturated with a volatile fluid (see figure 2). The operation of a heat pipe combines two principles of physics: vapor heat transfer and capillary action. Vapor heat transfer is used for transporting the heat energy from the evaporator section to the condensor section. Capillary action then returns the condensate back to the evaporator section. The working fluid absorbs the heat energy received at the evaporator section, transports it through the pipe, and releases it at the condensor end. Since evaporation and condensation take place at essentially the same temperature, the heat pipe operates almost isothermally [4]. For example, a thermal power of 11000 watts was carried 27 inches by a one inch diameter heat pipe with a temperature loss so small it was difficult to measure accurately. By way of comparison, a copper block nine feet in diameter and weighing about 40 tons would be required to produce the same result. [8]

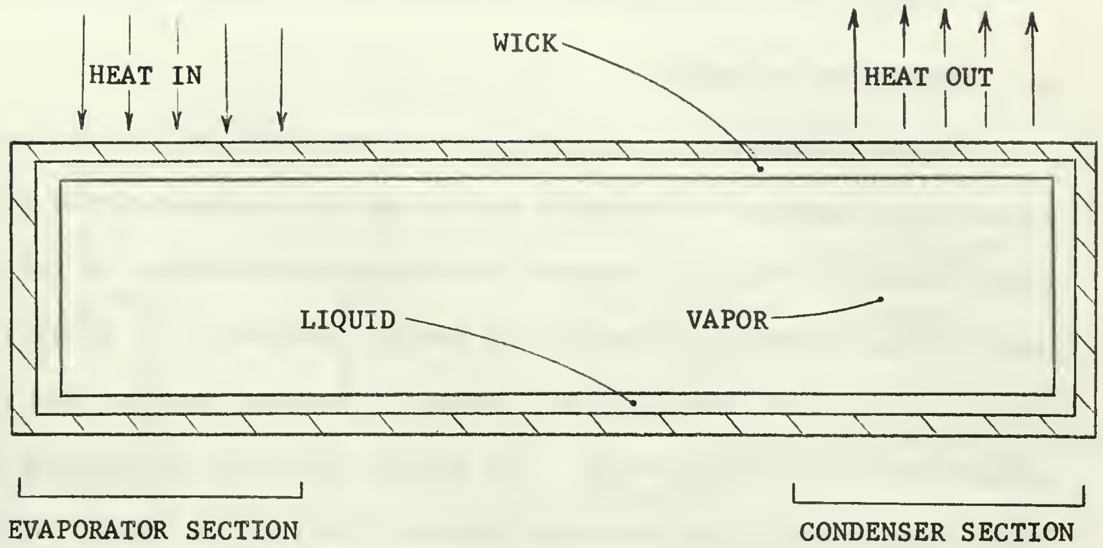


Figure 2

(Basic Components of the Heat Pipe)

The objective of this thesis was to parametrically analyze the feasibility of adapting the heat pipe to a deep sea RTG and to compare the design results using the heat pipe to an existing RTG design (SNAP-21).

II. BASIC DESIGN OF PROPOSED RADIOISIOTOPIC THERMOELECTRIC GENERATOR

A. COMPONENTS OF DESIGN

Figure 3 contains a cross section of the proposed RTG system. The major change made to the SNAP-21 design was the implementation of a heat pipe to enhance the heat transfer from the heat generated in the annular fuel pellet to the hot plate of the annular generator. A tubular geometry was used for the heat pipe primarily because experimental data exists for this configuration. The annular geometry of the fuel pellet and thermoelectric generator was necessary to provide enough surface area for efficient heat transfer to and from the heat pipe.

In order to get a meaningful comparison between designs, this analysis used the same materials as used in the SNAP-21 design. The biological shield is made of depleted Uranium with 8% Molybdenum added to shift the crystalline phase change of Uranium from 1300°F to 1800°F. Depleted Uranium is also a much better shield per weight than any other shielding material exhibiting similar strength. Safety requires that the fuel does not rupture its container under any accident. Thus, Hastelloy C is used as the fuel capsule due to its weldability and high tensile and yield strengths. Strontium-90 is the fuel used because of its relatively cheap cost and availability. The pressure vessel is made of 721 Titanium because of its high strength per weight. The heat pipe is made with stainless steel containing sodium as a working fluid because of the expected operating temperature of 1300°F. To make the heat pipe as effective as possible [4], a small capillary pore radius of .02 inch was chosen. From figure 5 of reference [4], the pressure head developed in

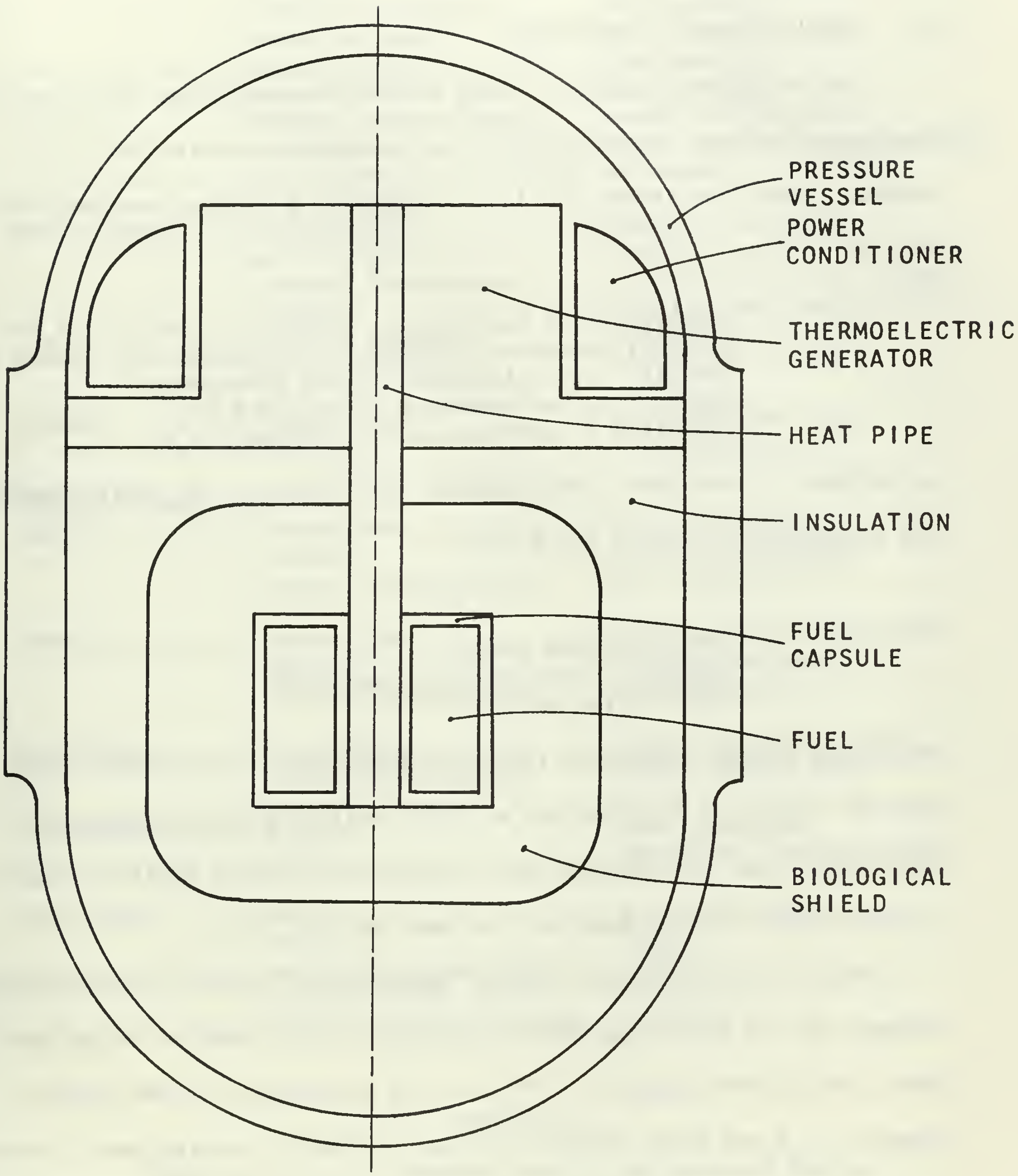


Figure 3
(Basic features of the proposed design)

the sodium heat pipe was estimated to be .09 psi. These material specifications are given in table 2 [12].

B. IMPOSED DESIGN RESTRICTIONS

Due to its environment, a deep sea RTG has specified conditions of operation, design, and fabrication not ordinarily required of such a device. These conditions as listed in SNAP-21 B Program quarterly report #1 [12] are:

Temperature of surrounding water.......34.5°F $\pm$ 6.5°F
External pressure....10,000 psi or 22,500 feet (ocean depth)
Humidity ....100% max in salt atmosphere
Shock........an excursion producing 6 g's
Vibration ....an excursion producing 3 g's

In addition to the above environmental restrictions, the desired mechanical properties of a deep sea RTG are:

Fully shielded device
Removable thermoelectric generator
Life of five years

The Atomic Energy Commission (AEC) has specified in its safety standards the condition required for a fully shielded device. This condition states that the external dose rate due to nuclear radiation must be less than 200 milli Roentgen per hour (MR/hr) [13].

There were no attempts made to redesign the generator thermocouple elements so the specifications as presented by the SNAP-21 design were those used in this analysis. The hot end temperature of the thermoelements (T_H) was held constant because the SNAP-21 design specifications for the thermoelements were not available for temperatures higher than 1100°F. These thermocouple element materials are listed in table 2.

Those factors held constant in this analysis were: the materials and their properties, the generator specifications (output at beginning

FUEL...........	composition	SR-90
	chemical form	$SrTiO_3$
	melting point	1900°C
	max. operating temp	1425°F
	density	3.7 gm/cc @ 70°F
	specific activity	33 curies/gm
	specific power	0.21 watt/gm
	power density	0.8 watt/cc
	specific heat	0.143 BTU/gm°F
	thermal conductivity	0.0132 cal/sec-cm°C
	radiation	gamma due to bremsstrahlung
	half-life	28 years
FUEL CAPSULE....	composition	Hastelloy Alloy C
	melting point	2400°F
	thermal conductivity	10.0 BTU/hr-ft-°F @1150°F
	density	0.323 pounds/inch^3 @ 72°F
	tensile strength	121,000 psi @ 72°F
	yield strength	81,000 psi @ 72°F
HOUSING	composition	721 Titanium
	density	0.16 pounds/inch^3
GENERATOR COLD FRAME	composition	Tellurium Copper
	density	0.32 pounds/inch^3
	thermal conductivity	209. BTU/hr-ft-°F
SHIELD	composition	depleted Uranium 8% Moly
	density	.629 pounds/inch^3
	thermal conductivity	19 BTU/hr-ft-°F
INSULATION	composition	Linde Super Insulation
	thermal conductivity	0.0008 BTU/hr-ft°F
THERMOELEMENTS...	N-type	PbTe segmented
	P-type	$(BiSb)_2Te_3$ and PbTe-SnTe
HEAT PIPE	wall	Stainless Steel
	fluid	Sodium
	operating temperature	1300°F
	capillary pore radius	0.02 inch
	pressure head developed	0.09 psi

TABLE 2

(Materials Used in SNAP-21 Design and Proposed System)

of life of 13.8 watts), heat pipe diameter (1 inch), fuel capsule thickness (¼-inch), pressure vessel thickness (1 inch for the cylindrical walls and ½-inch for the hemispheres), heat loss through shield structural supports and generator insulation (47 watts), and the hot end operating temperature of the generator (1100°F).

Since the SNAP-21 design is an operating system and the materials used in the proposed design are identical with SNAP-21 specifications, this parametric analysis should give results comparable to the building of an operational system.

C. DESIGN VARIABLES

The parameters varied were the outer radii of the fuel, biological shield, and insulation (also forcing the length of the fuel pellet to vary).

Three mechanisms of the proposed RTG design (figure 3) are functions of the variable parameters. The changing of any one of the radii affects the safe level of the nuclear radiation at the outside of the pressure vessel (discussed in the Nuclear Radiation Analysis). Both the generator cold frame and insulation package heat transfer equations are basically functions of radial variations. Thus the thermoelement cold end operation temperature and the total system heat loss are also functions of the variable radii (these effects are clarified in section III).

III. ANALYSIS OF PROPOSED RTG DESIGN

The heat transfer was analyzed using steady state, constant property, radial heat conduction. The nuclear radiation was treated according to equations given in Etherington's Nuclear Engineering Handbook, SNAP-21 specifications, and the principle of superposition of dose rates.

A digital computer program was written to analyze this system. It takes into account these three effects as the outside radii of the biological shield, fuel pellet, and insulation are varied. Within the acceptable limits of the dose at the outside of the pressure vessel due to nuclear radiation (200 MR/hr $\pm$ 25 MR/hr), the weight of the system (excluding insulation and power conditioning unit) and the overall efficiency (at beginning of life) were calculated and plotted.

A. NUCLEAR RADIATION ANALYSIS

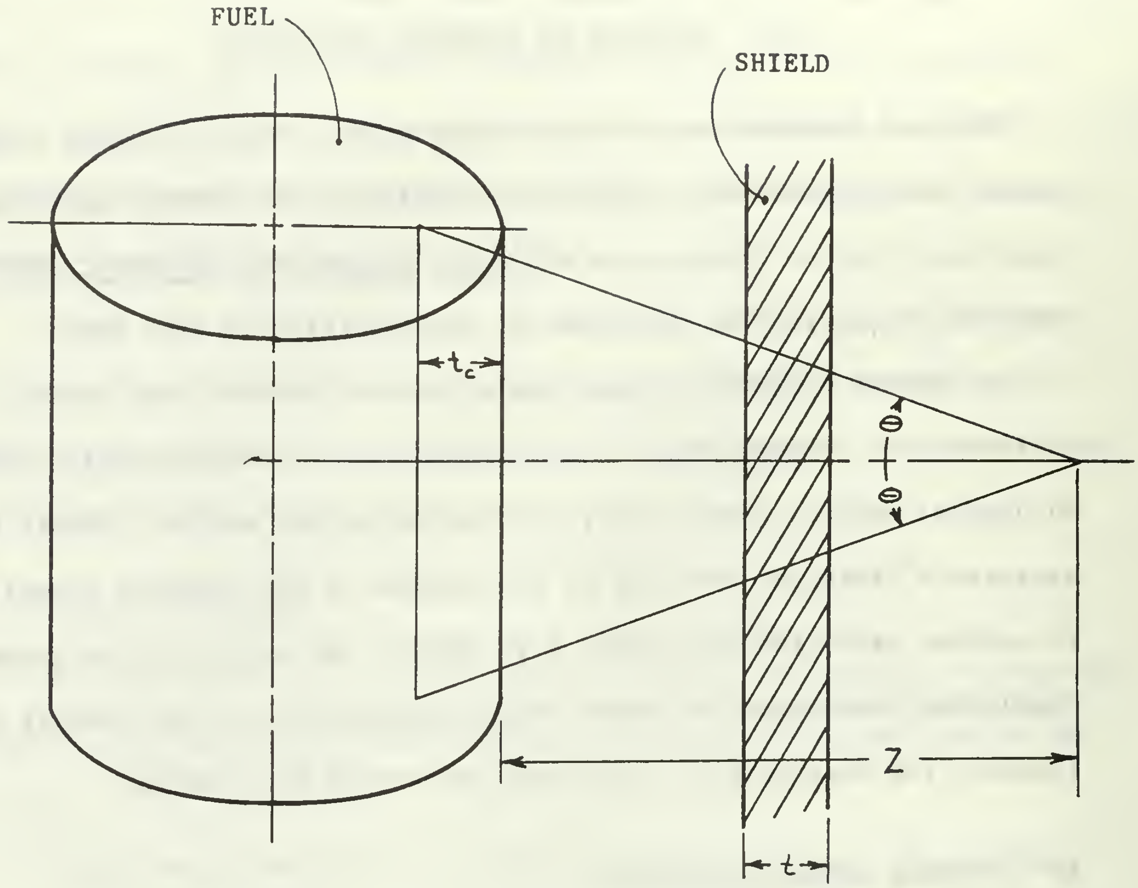
The analytical solution for the dose rate at a given distance from a finite length cylinder of radioactive material is given in Etherington's Nuclear Engineering Handbook, Chapter 7 [6]. This solution (figure 4) assumes a uniformly distributed source emitting radiation at only one energy and shielded by only one type of shielding material in the form of a slab. The RTG system as proposed in this design has four complicating variations.

1) The gamma radiation from the fuel has a continuous energy spectrum with an E_{max} of 2.18 ev.

2) There is a series of shielding materials present -- fuel capsule, biological shield, pressure vessel.

3) The fuel is an annular cylinder.

4) The shield is an annulus circumscribing the fuel pellet.



$$D = 6.95 \times 10^{-5} \frac{\mu_a}{\rho_a} EB\phi = KB\phi$$

$$\text{where } \phi = \frac{2Pa^2}{4(Z+t_c)} F(\theta, \mu t + \mu_c t_c)$$

P = source strength for volume source

μ = attenuation coefficient of shield

μ_c = attenuation coefficient of source

t_c = self absorption distance

t = shield thickness

$\frac{\mu_a}{\rho_a}$ = mass absorption coefficient of air

E = energy of nuclear radiation

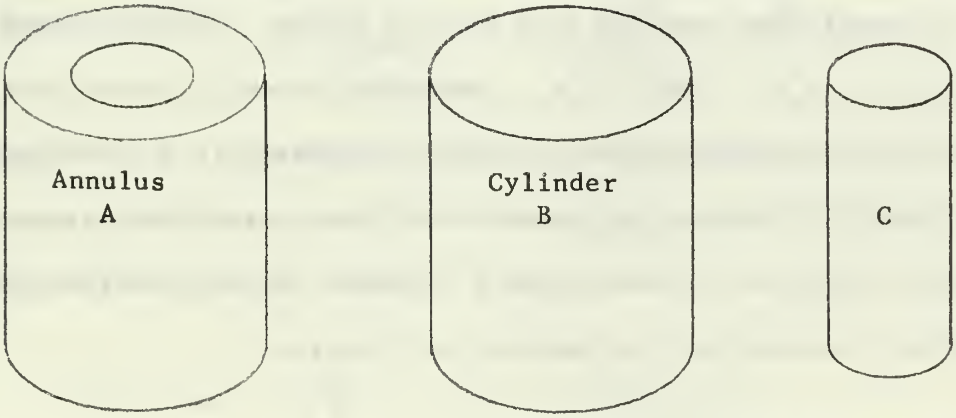
B = buildup factor

Figure 4
(Model employed to calculate dose rate due to nuclear radiation)

The first difference was handled by breaking the energy range up into ten equal intervals and considering each interval as one distinct group at the mean energy of that group. The dose rate was then calculated for each interval and summed over the ten energy intervals to get the total dose rate. The values of μ (attenuation coefficients) for Sr-90 fuel and the various shielding materials as a function of energy are presented in appendix A. Values of $F(\theta, \mu t + \mu_c t_c)$ & $\mu_c t_c$ are plotted in reference [11].

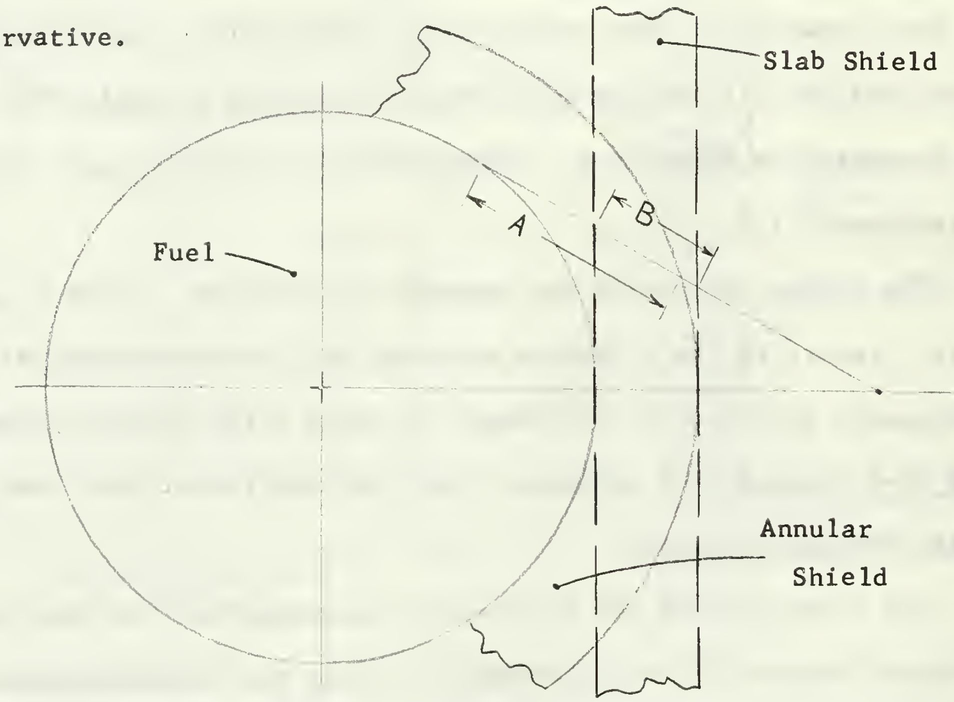
The second difficulty was removed by replacing μt by $\sum_i \mu_i t_i$, where i refers to the different shields, and then proceeding as usual. Experiments made by the 3-M Company in their first quarterly report SNAP 21-B Program [13] indicated that this analytical model was approximately 30% conservative.

The third problem was overcome by assuming that the dose rate due to different sources can be superimposed. Using the following sketch, the dose rate due to A equals the dose rate due to B minus the dose rate due to C.



Dose Rate Due to A = Dose Rate Due to B - Dose Rate Due to C

The fourth variation was analyzed through geometrical considerations. Using the following sketch, the annular shield presents more shielding material to the nuclear radiation than the slab shield proposed by Etherington's model. Thus the solution using a slab should be conservative.



Since A $>$ B, more shielding was present than that assumed and the proposed model was conservative.

Etherington's equation was programed on a digital computer (IBM 360) to handle the specific case of this design. Interpolations for F $(\Theta, \mu t + \mu_c t_c)$ and $\mu_c t_c$ were done assuming linear relationships. The computer program's estimated accuracy is $\pm$ 25 MR/hr (arrived at by checking computerized answers with hand calculated values). A numerical solution to Etherington's equation (as modified) is given in appendix A, as well as the computerized solution.

B. HEAT LOSS THROUGH INSULATION

The proposed RTG design has a series of finite length concentric annular cylinders restricting the heat transfer from the fuel pellet to

the surrounding water. In order to analyze the heat loss to the water it was assumed that the concentric annular cylinders were of infinite length. A cross section of the proposed RTG design is indicated in figure 5. The annular fuel pellet requires the solution of an internal heat generation, radial heat conduction equation. The remaining annular cylinders were cases of pure radial heat conduction. The analytical solutions for these two cases are derived in appendix B. The equations for the particular case of the proposed RTG were combined to find the heat transfer rate out, per unit length, $\left(\frac{Q}{\ell}\right)_{out}$, when the inside and outside temperatures (T_1 and T_6) are specified. This particular case is done analytically in Appendix B.

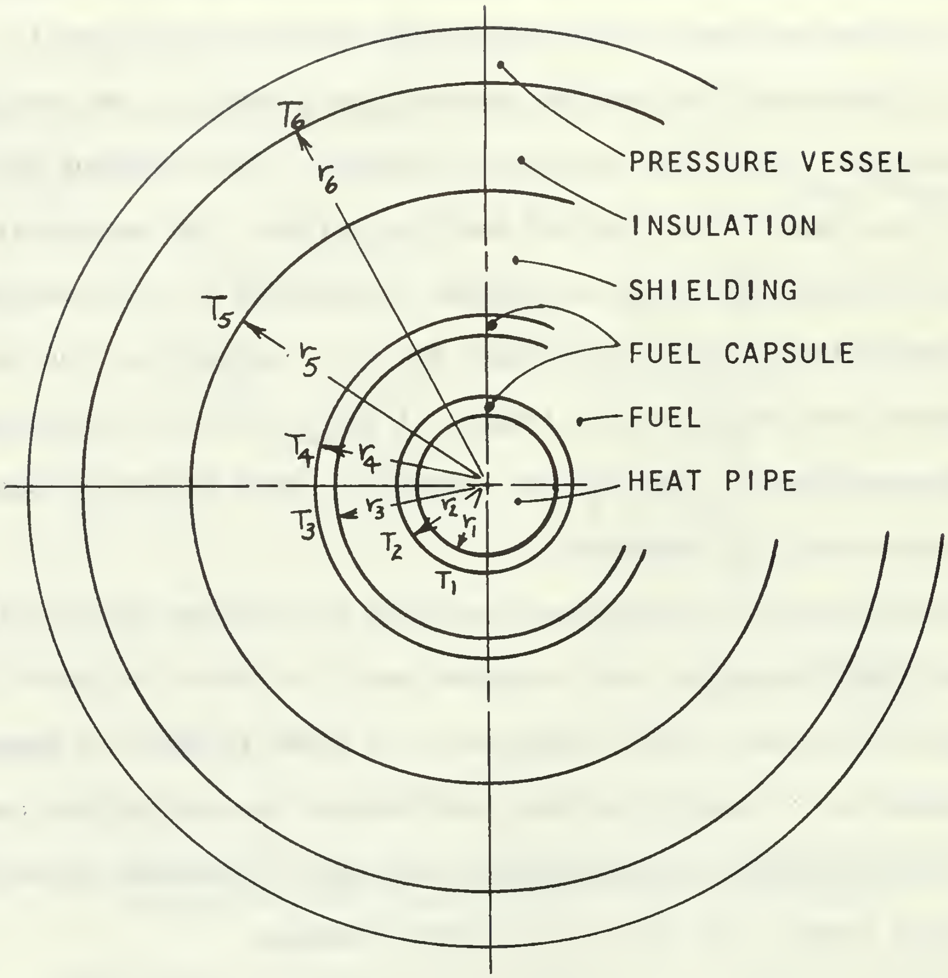
The adaption of this solution concerning an infinite length cylinder (or finite length cylinder with insulated ends) to that of a finite length cylinder necessitates a basic assumption. In order to make the assumption reasonable, an analysis of the ratio between the end surface area and the lateral surface area was made. Letting R = cylinder radius and L = cylinder length, the ratio of the areas becomes:

$$\frac{A_{ends}}{A_{lateral}} = \frac{2\pi R^2}{2\pi R L} = \frac{R}{L}$$

Basing the total heat transfer of the finite length cylinder on an area basis, the actual heat transfer (since $\left(\frac{Q}{\ell}\right)_{out}$ is calculated according to the equation given in Appendix B) is:

$$Q_{actual} = \left(\frac{Q}{\ell}\right)_{out}\left[L\left(1 + \frac{A_{ends}}{A_{lateral}}\right)\right]$$

$$= \left(\frac{Q}{\ell}\right)_{out}\left[L + R\right]$$



T's represent temperatures at interfaces

k_f = thermal conductivity of the fuel

k_c = thermal conductivity of the fuel capsule

k_s = thermal conductivity of the shielding material

k_i = thermal conductivity of the insulation

Figure 5
(Cross section of proposed design)

Q_{actual} lies between 5 and 11 watts, thus making the initial assumption of insulated ends (infinite length) close to correct. For values of R such that R $\ll$ L, the lateral surface area is much larger than the end surface areas. For these cases the heat transfer rate out the end areas would be negligible.

C. GENERATOR COLD FRAME HEAT TRANSFER

Tellurium Copper was the material used for the cold frame due to its high thermal conductivity of 209 BTU/hr-ft-°F. The basic design considers the heat transfer from the cold end of the thermoelements to the outside water as radial heat conduction with constant properties. The heat conduction equation for an annulus is given below [2]:

$$Q_{\text{transferred out}} = 2\pi k L \frac{(T1-T0)}{\ln(R0/R1)}$$

where R0 = outer radius
R1 = inner radius
T1 = temperature at radius R1
T0 = temperature at radius R0
L = length of annulus
k = thermal conductivity

For the assumed model shown in figure 7;

T1 = cold end temperature of thermoelements
R1 = 1.3 inches = radius of thermoelements cold end
T0 = 505°R outside temperature of annulus
L = 1 inch

The temperature variation in the radial direction was approximately from 70°F at a radius of 1.3 inches, to 45°F at the outer radius R0; over such a small range of temperatures the constant properties assumption is a valid one.

The shape of the generator cold frame can be seen in figure 6. Since both the upper and lower surfaces are insulated, the heat transfer is

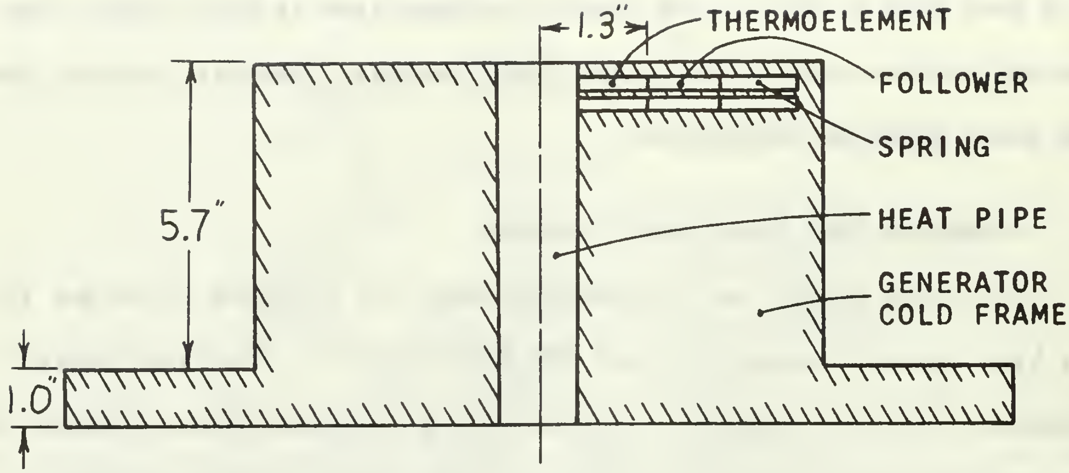


Figure 6
(Cross section of generator cold frame)

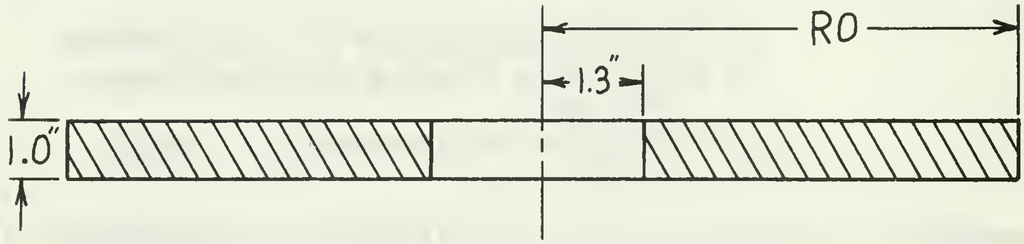


Figure 7
(Geometry assumed for heat transfer through generator cold frame)

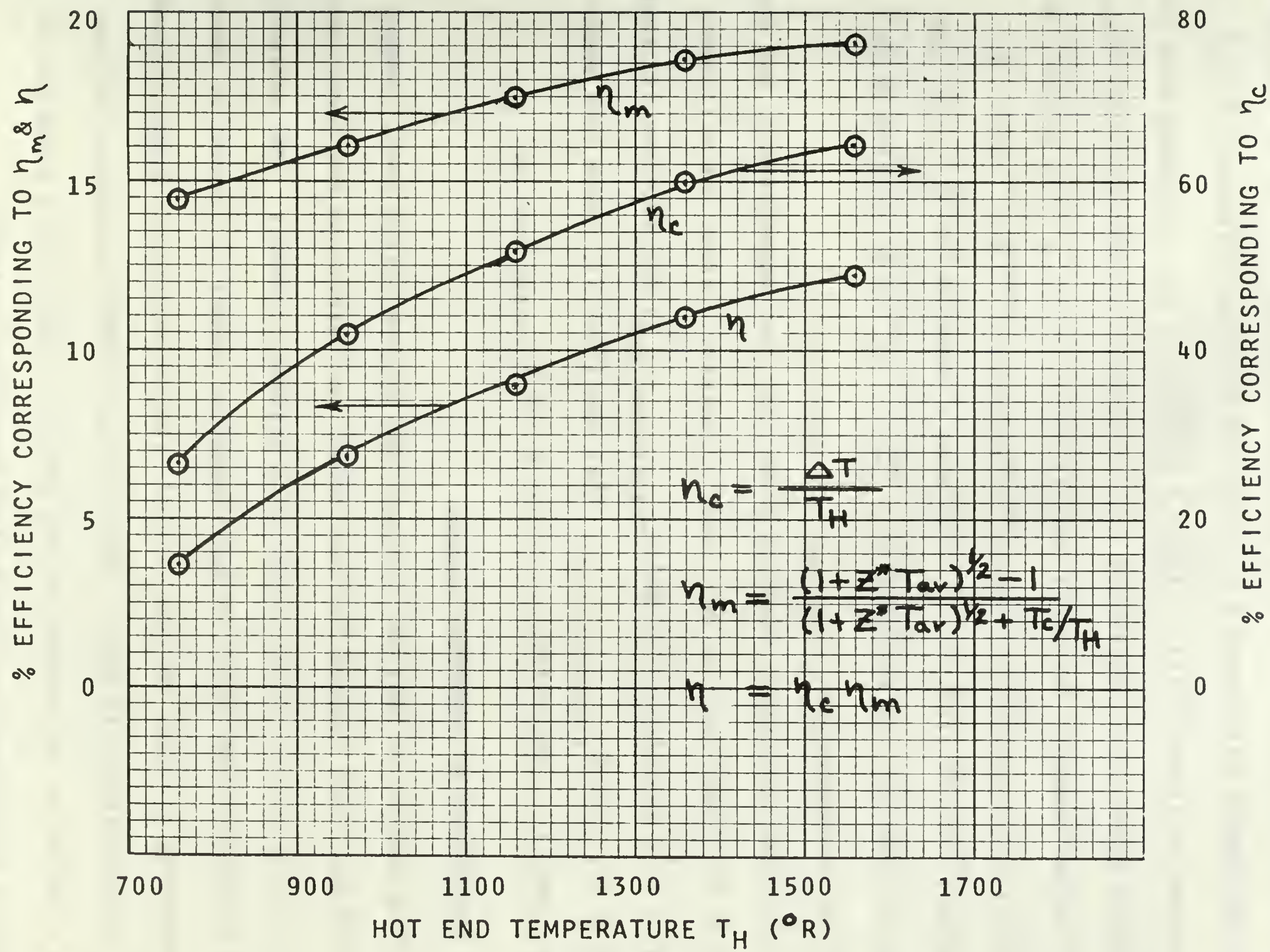


Figure 8
(Efficiencies vs. hot end temperature of SNAP-21 thermoelements)

assumed to take place in the configuration shown in figure 7. The thermal gradients in the axial direction in the figure 7 model are small and the proposed model assumes them negligible.

The efficiency (η) of a thermoelectric generator can be divided into the Carnot efficiency (η_c) and the material efficiency (η_m) as indicated in figure 8 [1]. Figure 8 shows that η_m increases with increasing temperature difference (ΔT) between the hot and cold ends of the thermoelements. The model used is one where η_m was constant and was thus conservative with respect to increasing ΔT. With η_m constant, the efficiency (η) is then a function of η_c only, and with the same hot end temperature (T_H), η is a function of ΔT only (or more exactly, T1).

The heat conduction equation shows that the temperature T1 and the heat to be transferred out are linearly related. Since the efficiency (η) is a function of T1 and $Q_{transferred\ out}$, the solution is iterative (i.e., pick $Q_{transferred\ out}$, this specifies T1, which then specifies a new η, which then specifies a new $Q_{transferred\ out}$).

D. DERIVATION OF COMPUTER PROGRAM

The subroutine HEAT was derived from the analytical model assumed for the heat loss through the insulation, and determines the total system heat loss (since all other losses were assumed constant). The subroutine QGEN determines the amount of fuel needed to supply 13.8 watts of power at beginning of life, and was derived from the analytical model assumed for the generator cold frame. The subroutine DOSE determines the dose rate in MR/hr at the surface of the pressure vessel for a given set of variables (developed from the Nuclear Radiation Analysis).

The flow chart in figure 9 shows that a given set of radii were picked and a total system heat loss (FUELS) was assumed. The subroutine QGEN then calculated the required amount of fuel needed to fulfill the design output (FUELG). The total required amount of fuel was then given by:

$$FUELT = FUELS + FUELG$$

Since the actual total system heat loss was obtained from an iterative process, a new value for the total system heat loss (QOT) was calculated. QOT was then compared to the assumed value (FUELS). With a positive answer to the IF statement the dose rate was then calculated by the subroutine DOSE, and the printable output limited to the range:

$$175 \text{ MR/hr} < \text{dose rate} < 225 \text{ MR/hr}$$

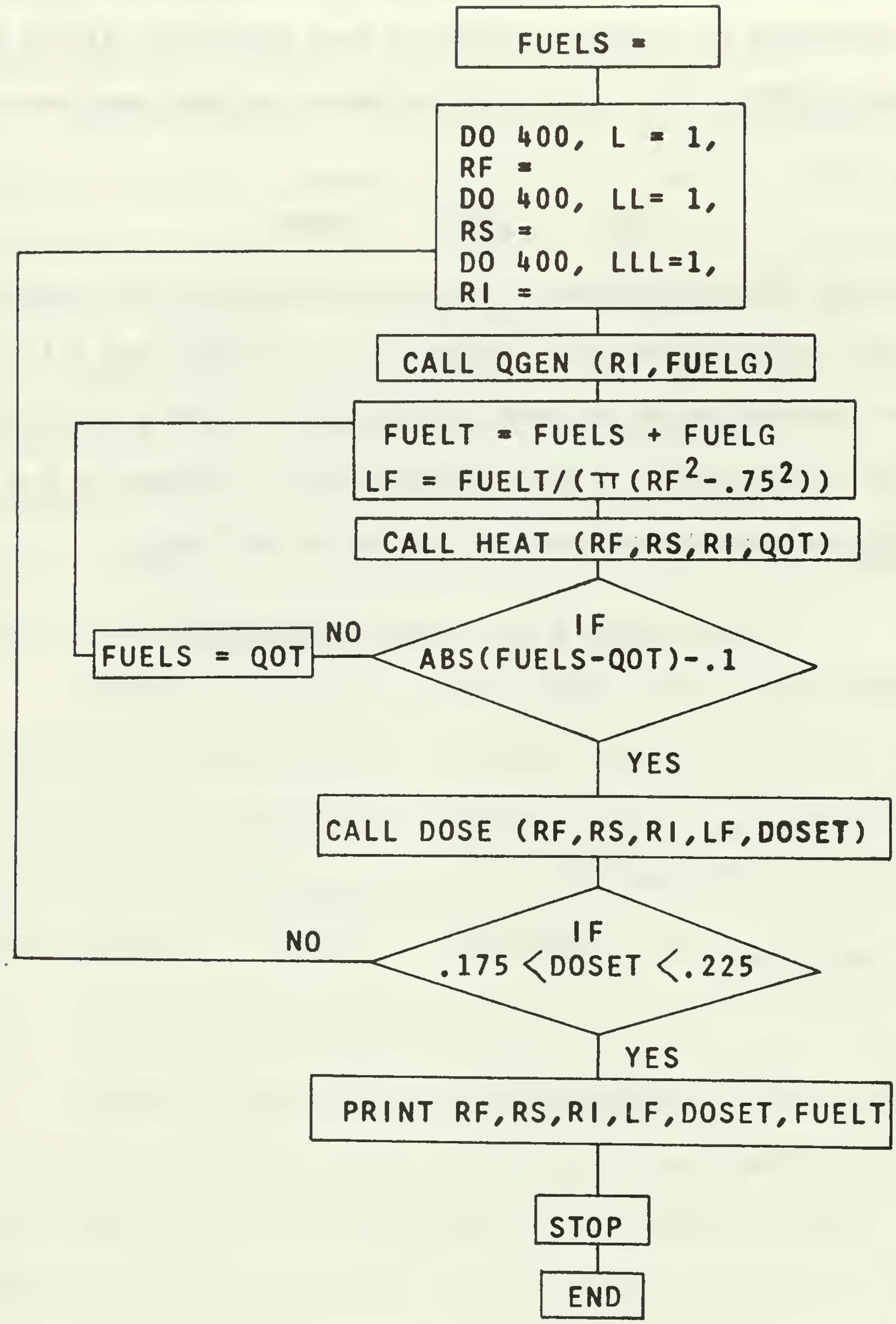


Figure 9
(Computer program flow chart)

IV. RESULTS AND DISCUSSION

Limiting conditions were imposed on the proposed RTG design due to AEC regulations specifying a safe maximum external dose rate of 200 MR/hr. For a given set of dimensions, the dose rate at the outer radius of the pressure vessel was calculated (using the computer program) with an assumed accuracy of $\pm$ 25 MR/hr. Any information regarding total weight or overall efficiency of the RTG was likewise limited to a range of dose rate (175 MR/hr to 225 MR/hr). Most graphs have these corresponding ranges in dose rate plotted. Note that in the following discussion, weight refers to weight of major components, which is equal to total weight minus weight of insulation and power conditioning units.

Figures 10 through 15 show values of weight versus fuel radius for constant values of insulation thickness. The information contained in these graphs indicates that there is a fuel radius where a minimum weight is reached for each value of insulation thickness. Knowing that the weight of various components are functions of the fuel radius and length (i.e., the fuel surface area), a minimum is expected. In the case of a solid cylinder, with a fixed volume, there is a set of dimensions where the surface area is a minimum (i.e., diameter = length).

When values of weight versus insulation thickness at constant values of fuel radius are plotted (figure 16), the radius of the fuel where minimum weight is reached is seen to always lie between 1.3 and 1.5 inches. When values of the fuel radius at which minimum weight is reached versus insulation thickness is plotted (figure 17), the general curve suggests using a slightly smaller fuel radius with increasing insulation thickness for minimum weight in the design.

Figure 18 plots overall efficiency at beginning of life versus fuel radius at constant insulation thickness and shows two aspects of the design:

1. Overall efficiency increases non-linearly with increasing insulation thickness.

2. Maximum efficiency is reached somewhere between a fuel radius of 1.55 and 1.70 inches. The maximum efficiency is never located where the minimum weight occurs.

Thus it was never possible to combine minimum weight with the maximum efficiency for a specific value of insulation thickness.

A plot of efficiency versus insulation thickness (figure 19) shows a non-linear increase in efficiency with insulation thickness. Therefore the greatest gain in efficiency resulted from the initial addition of .02 inches of insulation.

In order to get some comprehensive results it was necessary to plot minimum weight and the efficiency at minimum weight versus insulation thickness. Figure 20 shows that neither the minimum weight nor the efficiency are linear functions of insulation thickness until an insulation thickness of 1.6 inches is reached. This is recognized when the percentage increase in both minimum weight and overall efficiency is plotted versus insulation thickness as in figure 21. Thus using 1.6 inches of insulation results in the greatest gain in efficiency at the lowest gain in weight.

The SNAP-21 design has a maximum fuel temperature of 1700°F. The proposed RTG, through the use of the heat pipe, has lowered this temperature to a range of from 1385°F to 1410°F.

The SNAP-21 design operates at 5% overall efficiency at the beginning of life, and has a total weight of 640 pounds. Allowing 60 pounds (as done in SNAP-21) for the weight of the power conditioning units and the

insulation, the design with the maximum total weight contains 613 pounds and has an overall efficiency at beginning of life of 5.415%. This is also the design with the maximum overall efficiency. The minimum total weight obtained for any of the proposed RTG's was 555 pounds and had an overall efficiency at beginning of life of 5.37%. If the RTG was designed with 1.6 inches of insulation, the overall efficiency at beginning of life would be 5.4% with a minimum total weight of 570 pounds. Thus the introduction of the heat pipe has two effects, increasing the overall efficiency at beginning of life and decreasing the total weight.

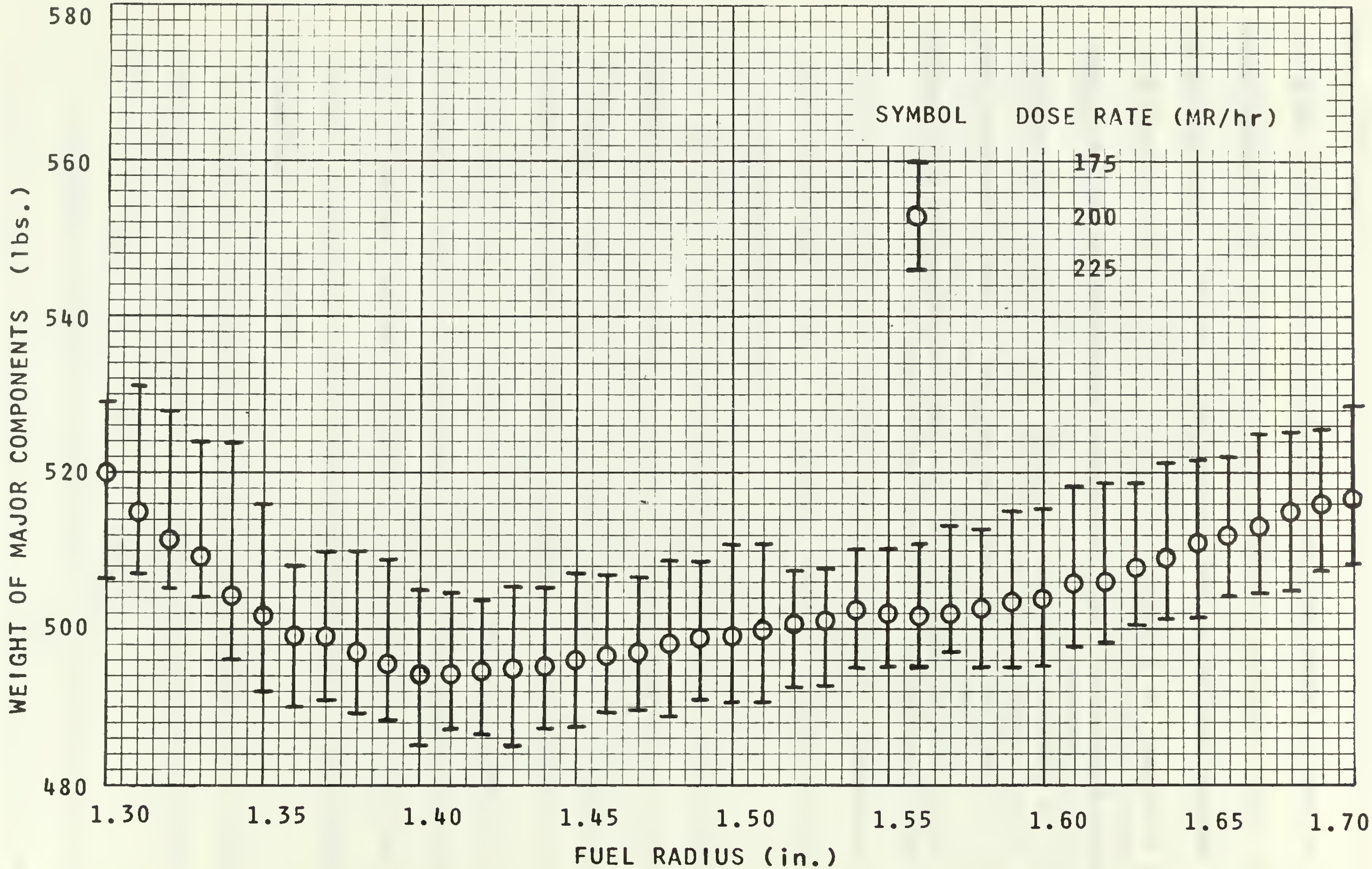


Figure 10
(Weight of major components vs. fuel radius at 1.0" insulation thickness)

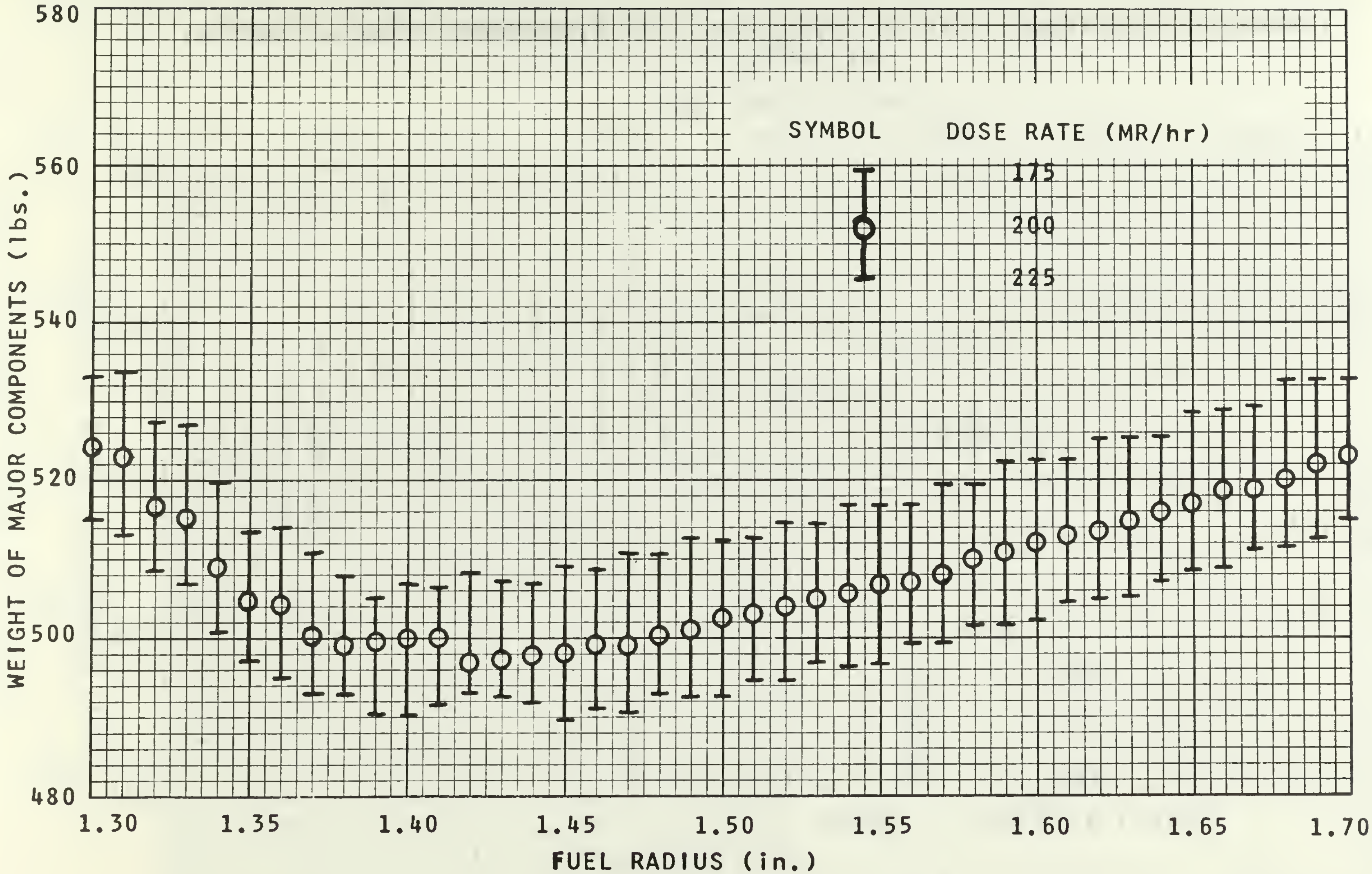


Figure 11
(Weight of major components vs. fuel radius at 1.2" insulation thickness)

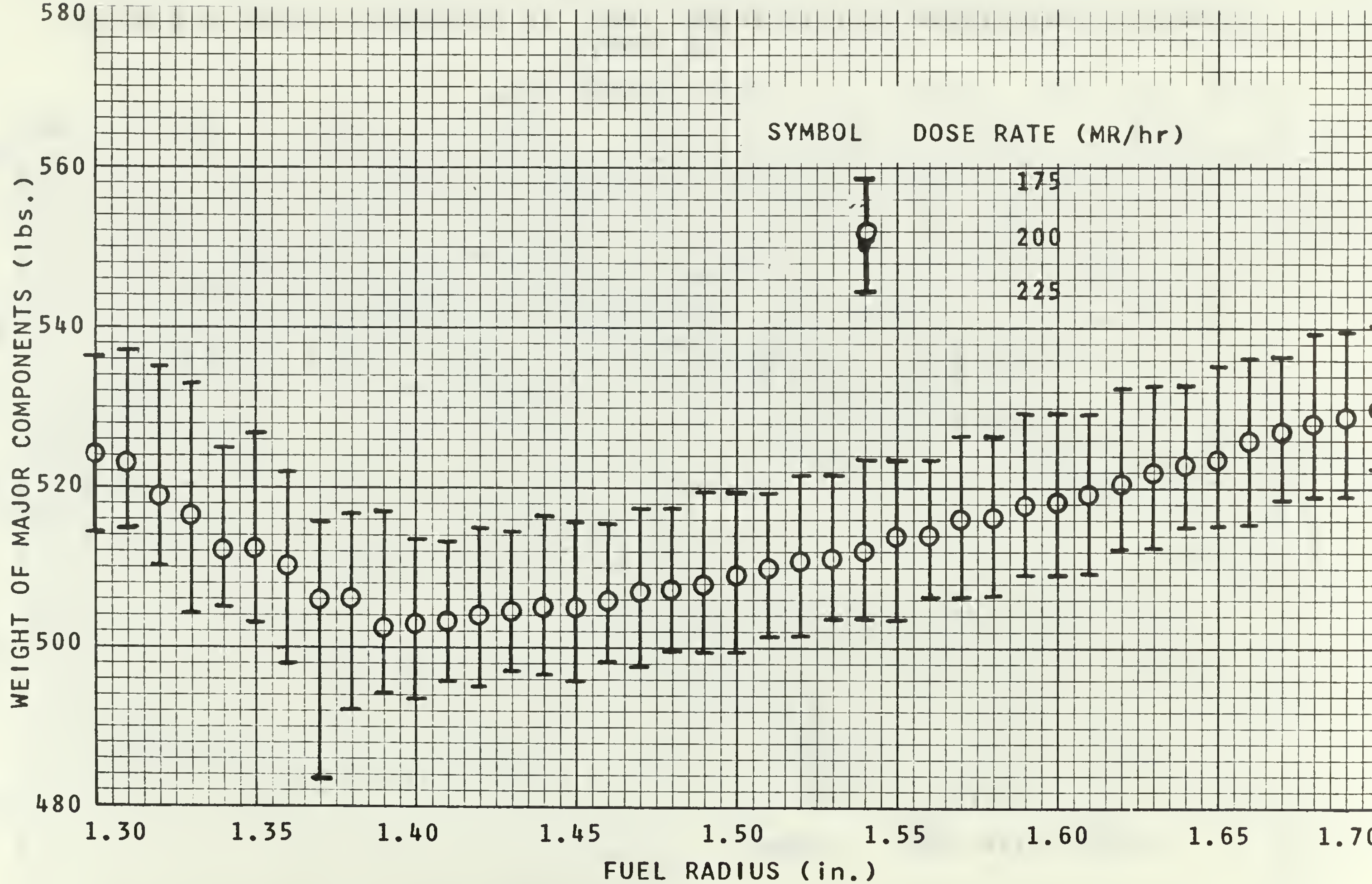


Figure 12
(Weight of major components vs. fuel radius at 1.4" insulation thickness)

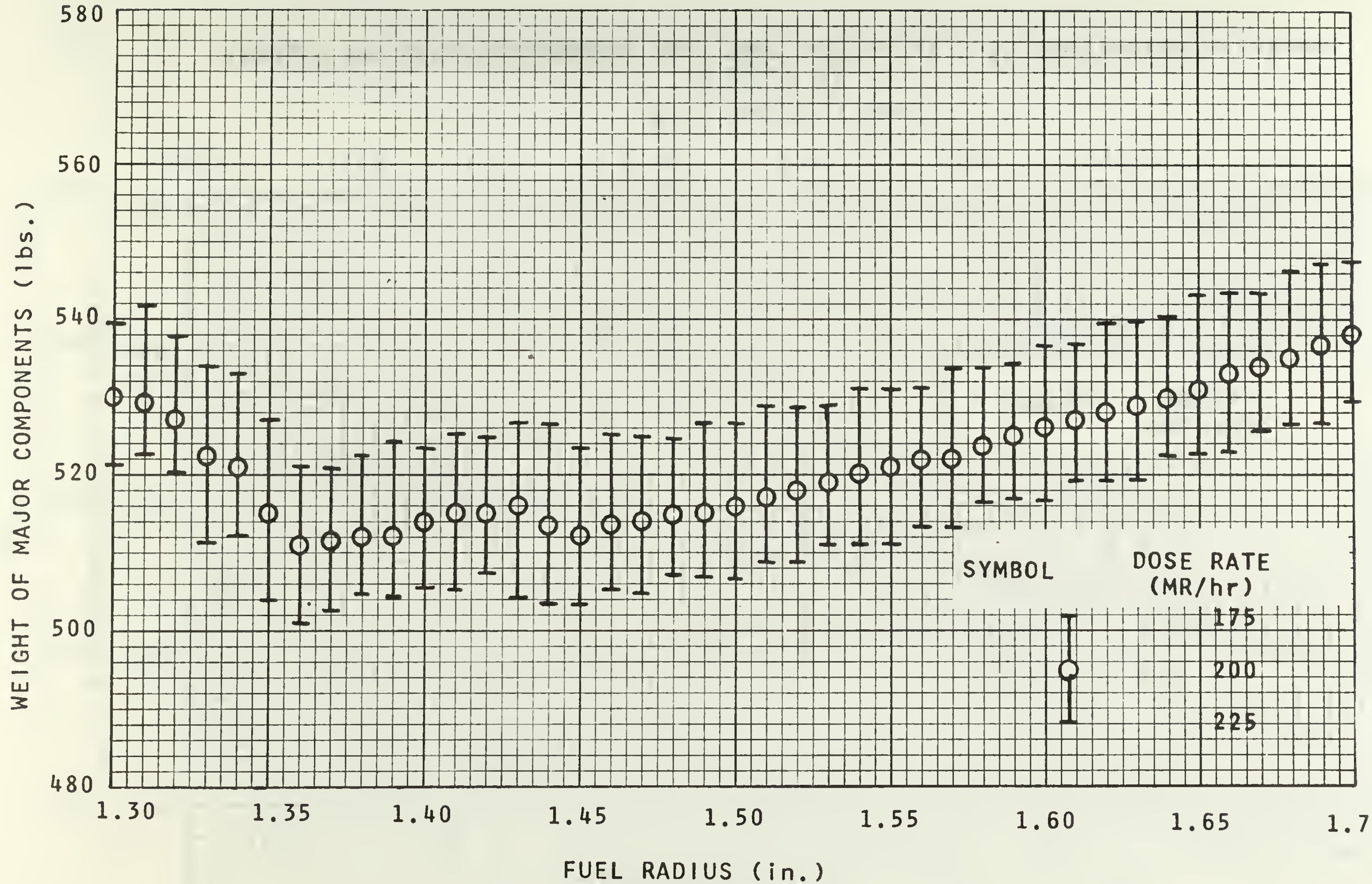


Figure 13
(Weight of major components vs. fuel radius at 1.6" insulation thickness)

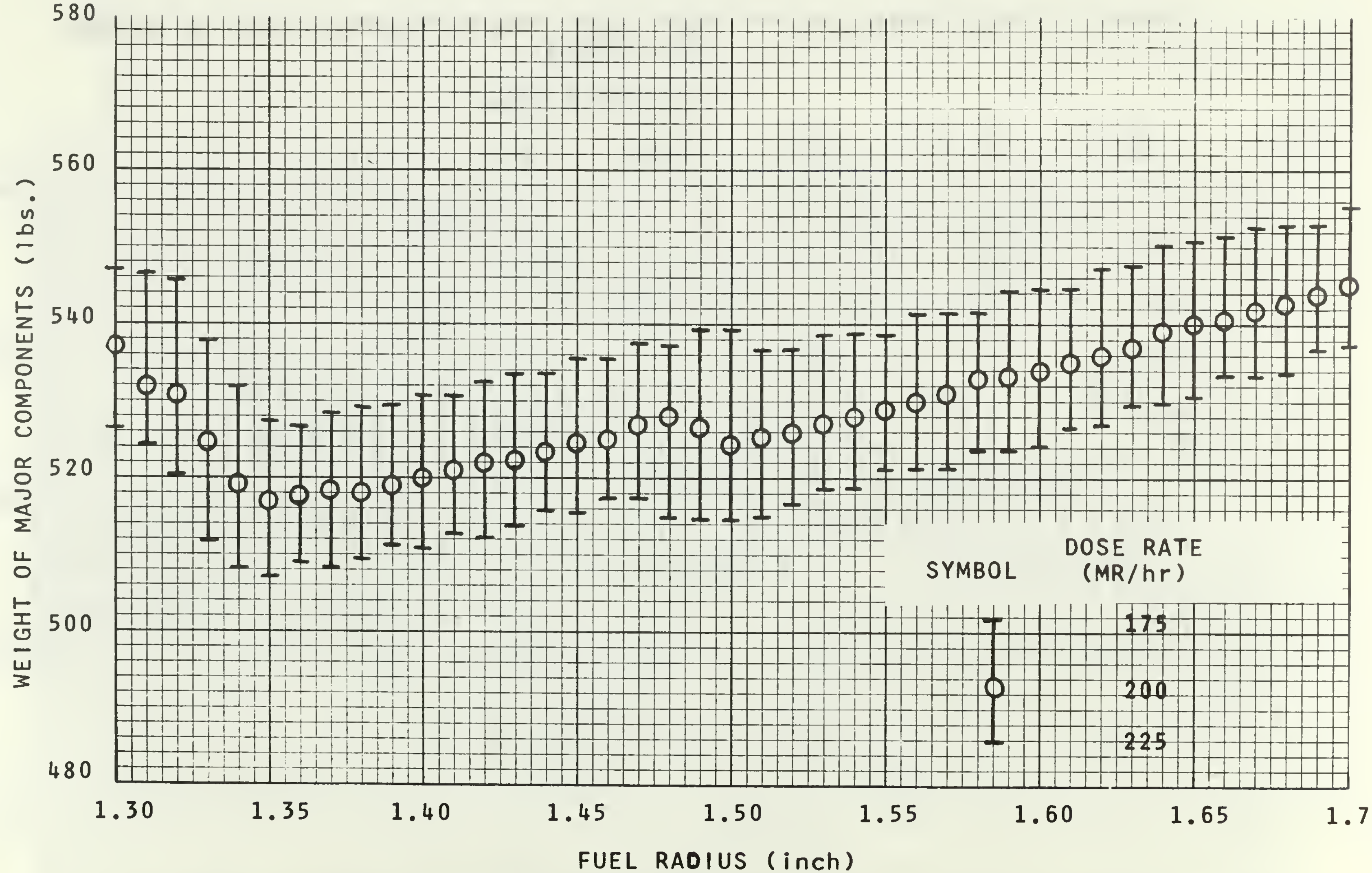


Figure 14
(Weight of major components vs. fuel radius at 1.8" insulation thickness)

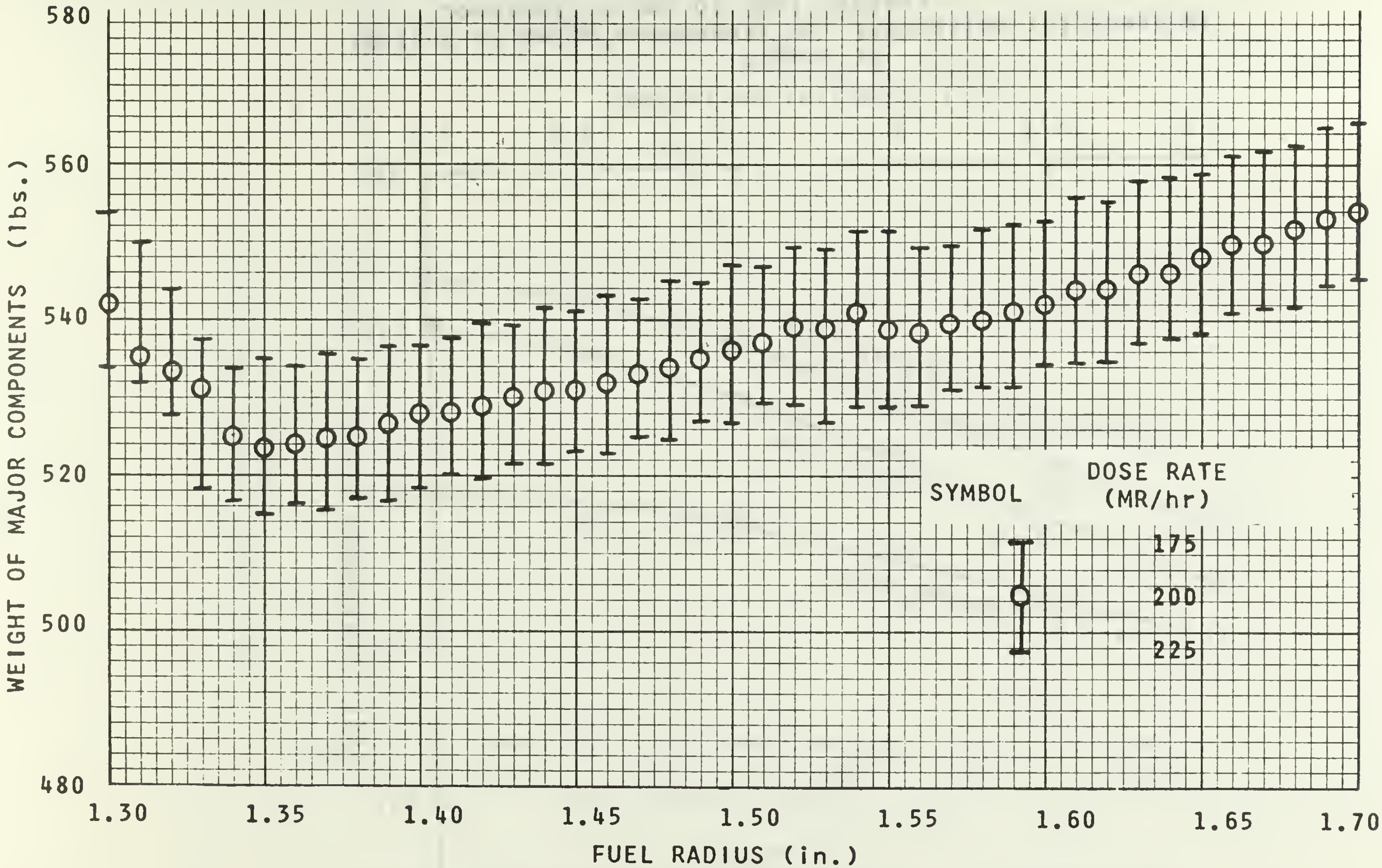


Figure 15
(Weight of major components vs. fuel radius at 2.0" insulation thickness)

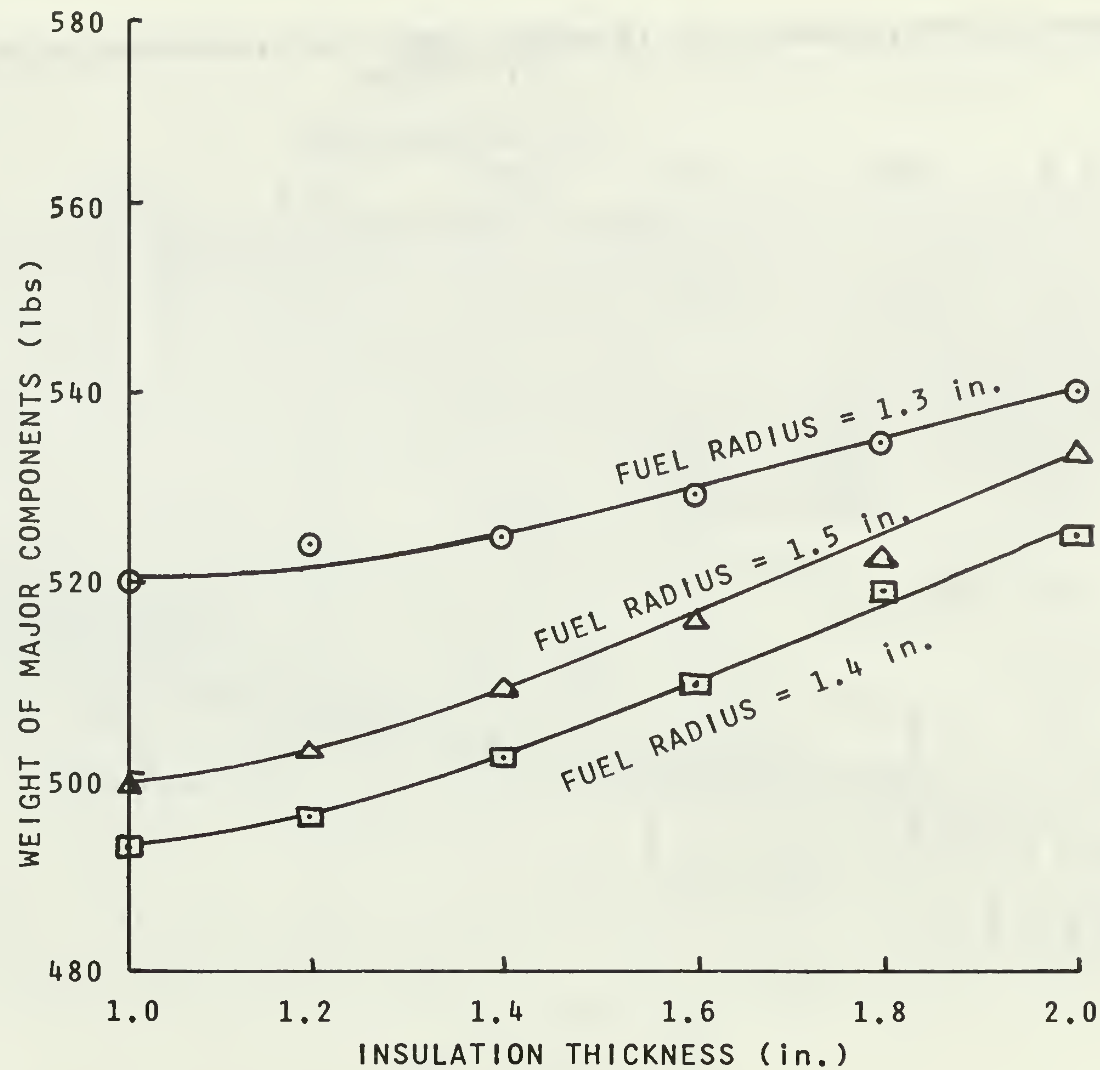


Figure 16
(Weight of major components vs. insulation thickness at constant values of fuel radius)

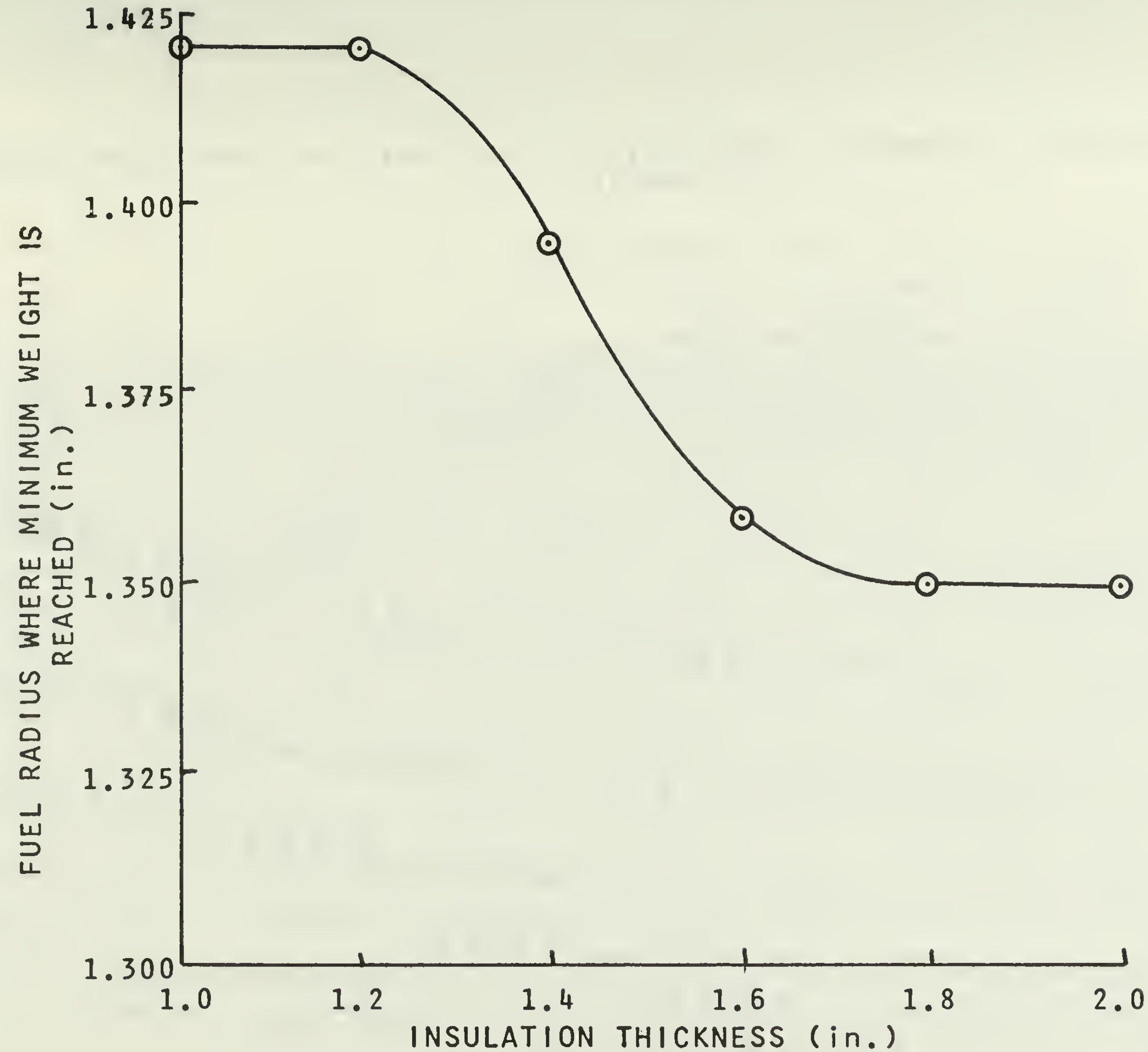


Figure 17
(Fuel radius at which minimum weight is reached vs. insulation thickness)

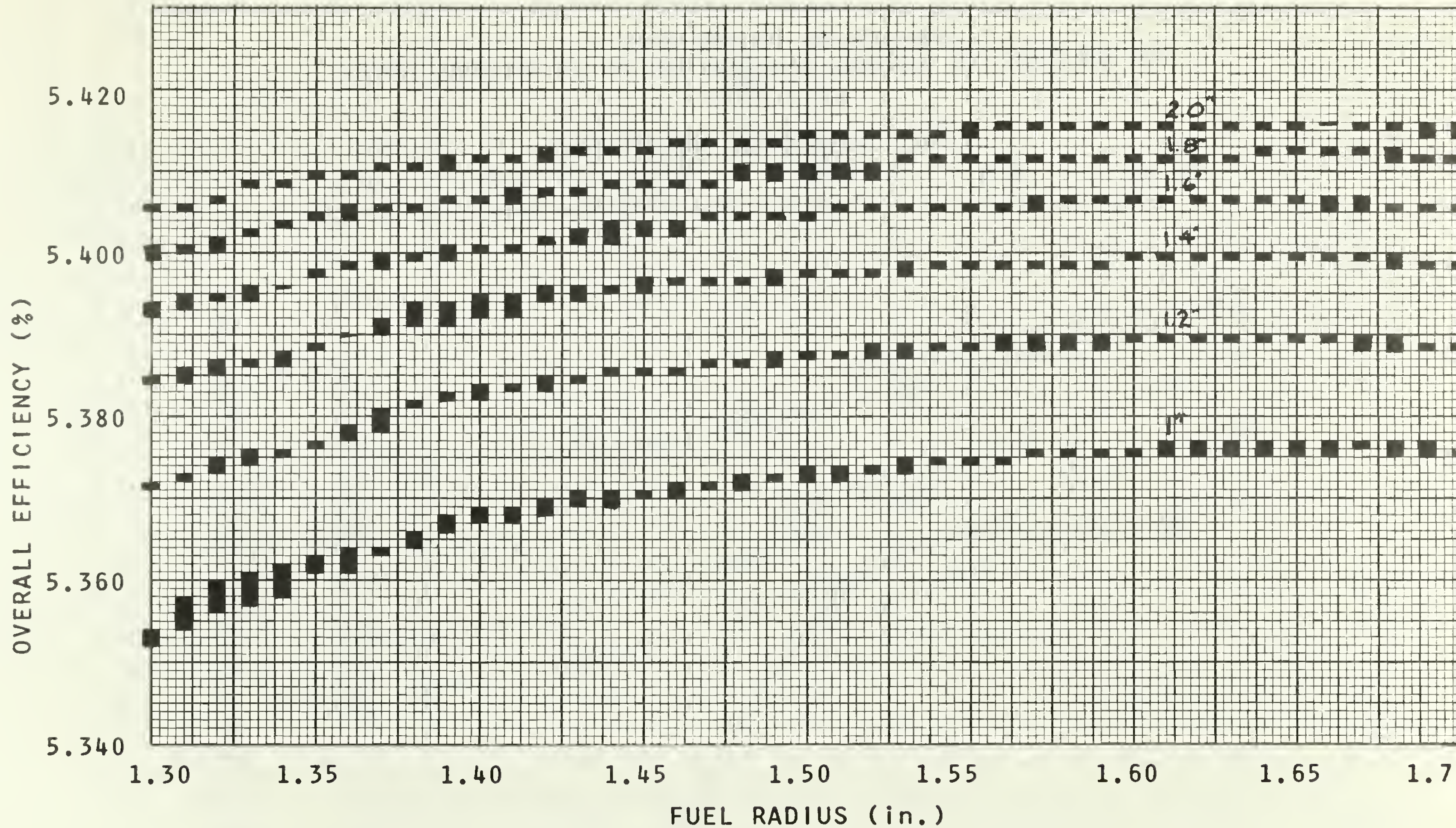


Figure 18
(Overall efficiency vs. fuel radius at constant values of insulation thickness)

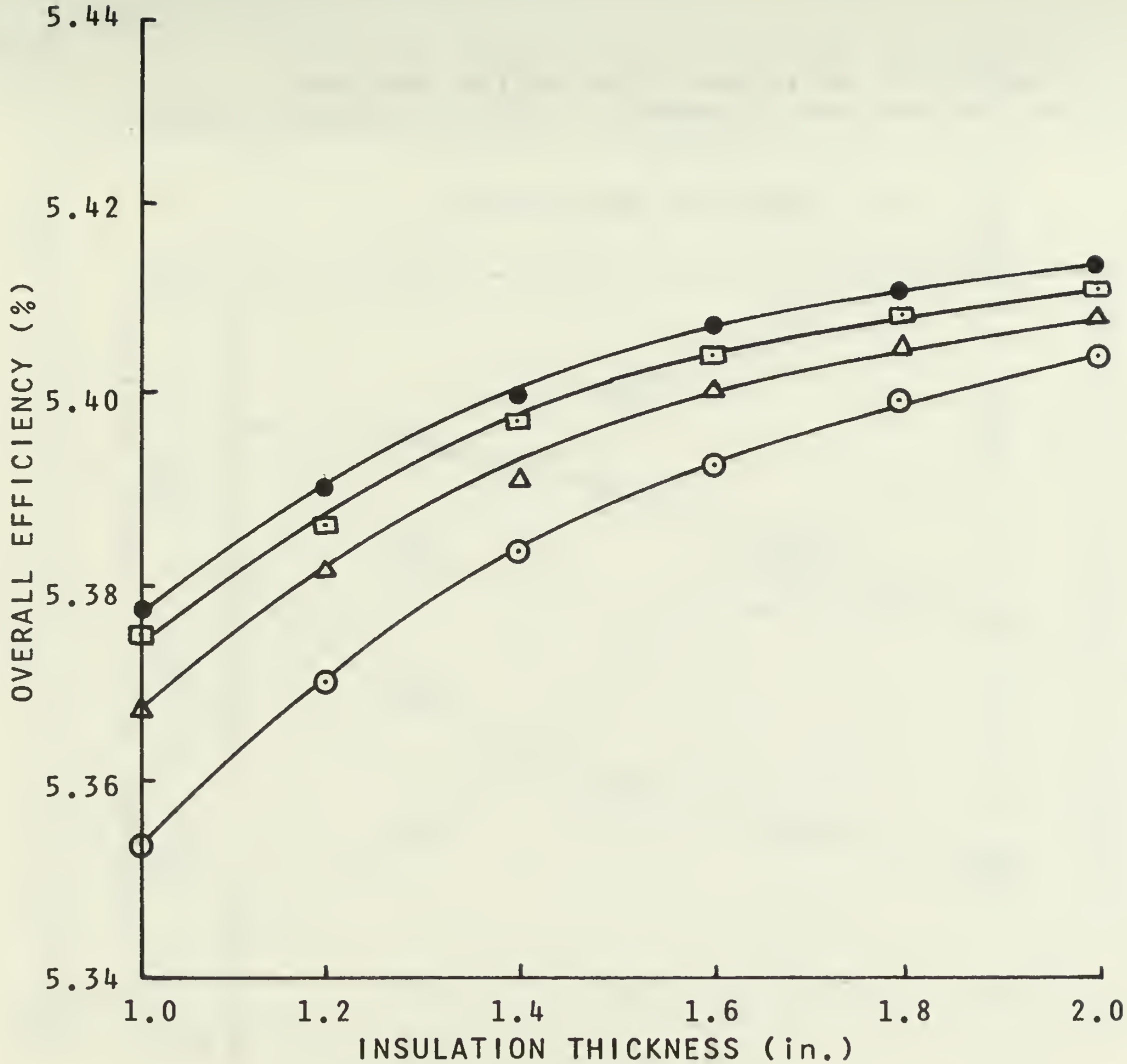


Figure 19
(Overall efficiency vs. insulation thickness at constant values of fuel radius)

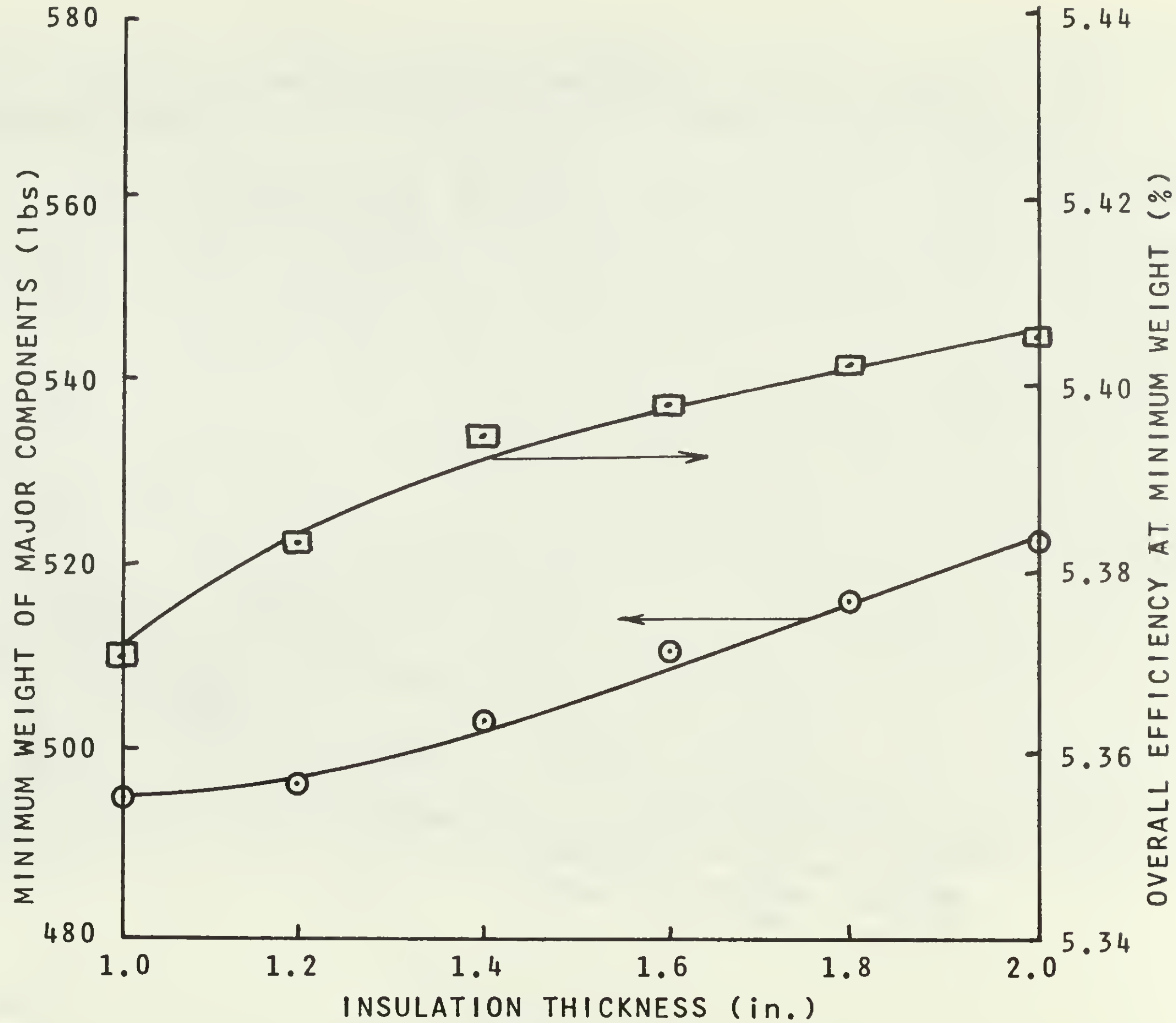


Figure 20
(Minimum weight of major components and overall efficiency at minimum weight vs. insulation thickness)

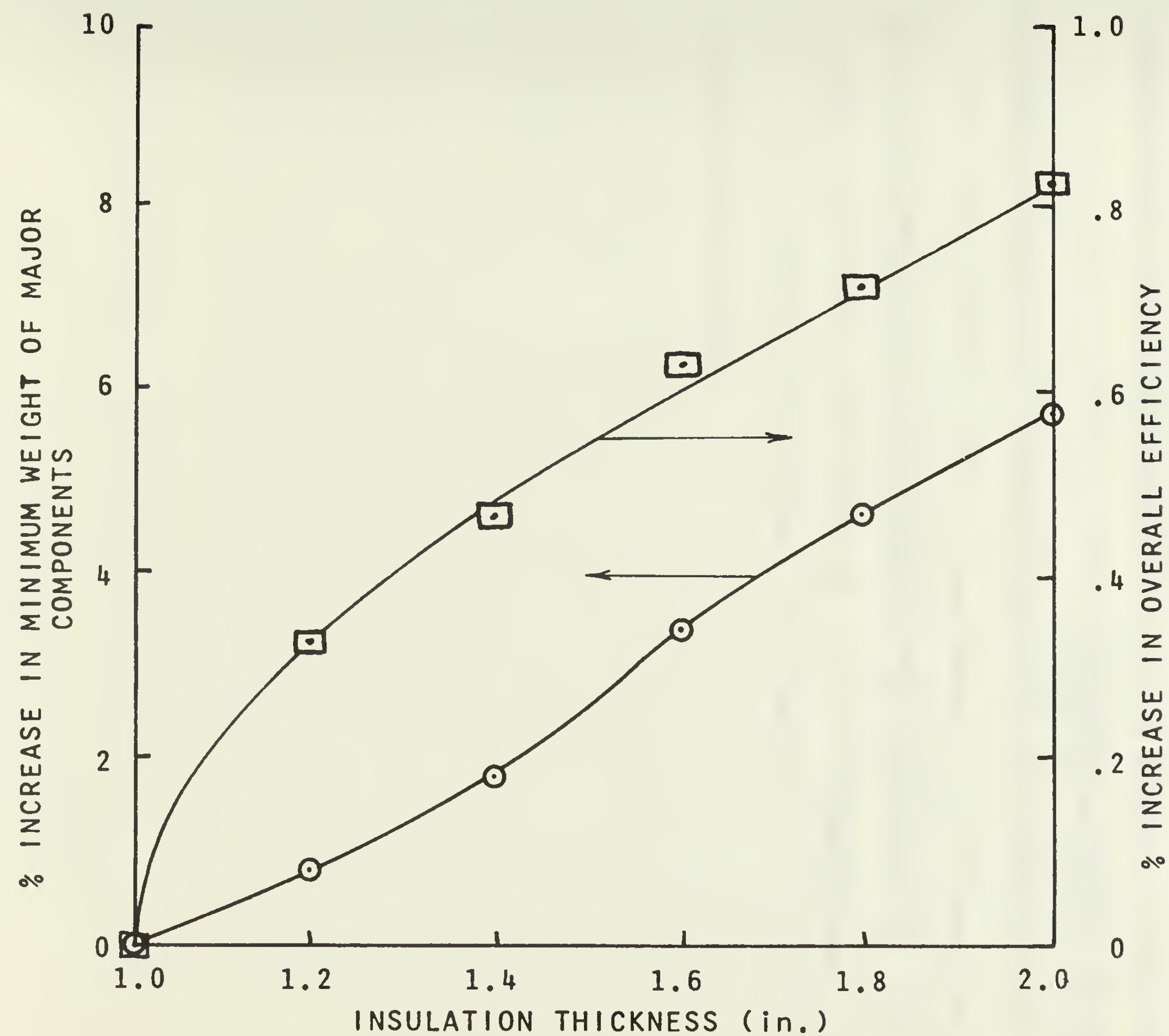


Figure 21
(Percentage increase in minimum weight of major components and overall efficiency vs. insulation thickness)

V. CONCLUSIONS

1) The use of a heat pipe in a RTG reduces the total weight and increases the overall efficiency (as compared to SNAP-21), while maintaining reliability and long life.

2) The design with minimum total weight has a different fuel radius than the design with maximum overall efficiency (at a specified value of insulation thickness).

3) The use of the heat pipe decreases the maximum temperature of the fuel from 1700°F to approximately 1400°F.

4) In most cases, the biological shield accounts for 40% of the total system weight.

VI. RECOMMENDATIONS

1) Perform experiments to verify the accuracy of the analytical solution for the dose rate due to the nuclear radiation.

2) Parametrically analyze the system for variable operating temperatures of the thermoelements.

3) Derive an analytical model for the heat transfer through the insulation surrounding the biological shield that doesn't assume infinite length geometry.

4) Analyze the relationship between the higher cost but lower amount of shielding required for an α emitting fuel.

5) Consider different heat pipe geometries for a more efficient heat transfer system.

APPENDIX A

NUCLEAR RADIATION ANALYSIS

Considering the model whose dimensions are shown in figure 22, tables 3 and 4 contain all the information necessary to calculate the dose rate due to the annular geometry fuel pellet. The final equation for the dose rate is (from figure 4) [13]:

$$D = KB\phi$$

where $\phi = \frac{P\alpha^2}{2(Z+t_c)}\left[F\left(\theta, \mu_c t_c + \sum_i \mu_i t_i\right)\right]$

K = constant given in figure 4

B = buildup factor

The computer program for this specific case calculates a dose rate of 118 MR/hr. The hand calculated dose rate is 134 MR/hr.

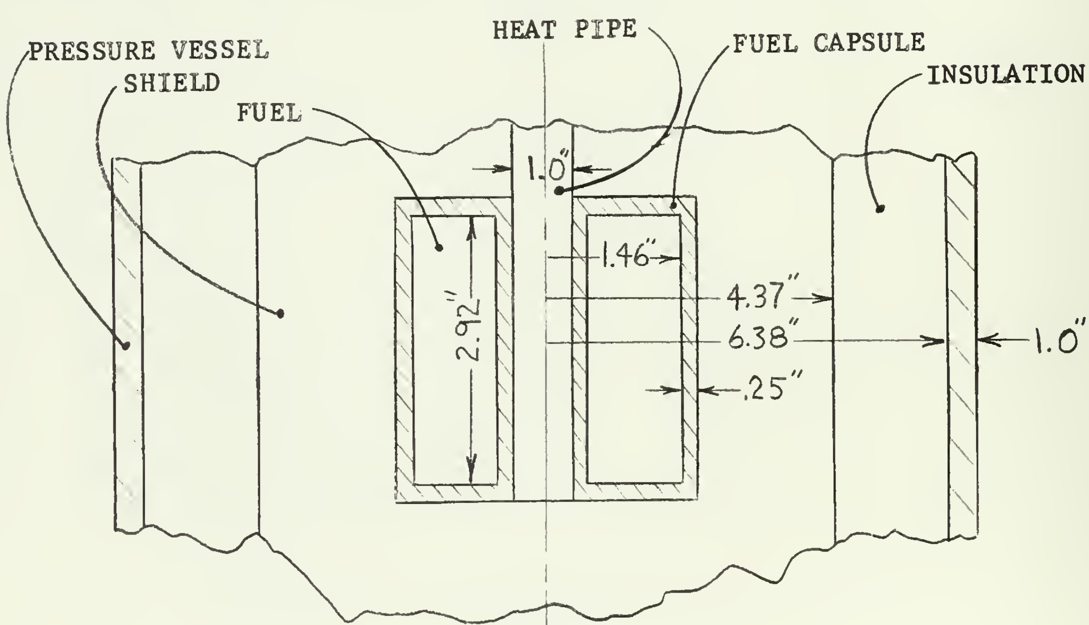


Figure 22

(Dimensions of example used in sample dose rate calculations)

Energy	μ_c	μ_H	μ_U	μ_x	$\mu_H t_H$	$\mu_x t_x$	$\mu_U t_U$	$\mu_c(a+Z)$	$\frac{\mu_a}{P_a}$	B	$K(10^{-6})$
0.11	1.153	2.91	102.0	1.07	1.85	2.63	690.	21.5	---	---	---
0.33	0.385	0.921	6.44	.47	.585	1.16	43.5	7.2	---	---	---
0.55	.294	.689	2.70	.368	.438	.904	18.2	5.5	---	---	---
0.77	.251	.581	1.72	.315	.369	.773	11.6	4.7	.070	2.5	3.1
0.99	.218	.514	1.26	.284	.326	.697	8.5	4.07	.060	2.8	3.4
1.21	.201	.467	1.10	.260	.297	.639	7.42	3.76	.054	2.7	3.8
1.43	.185	.436	.983	.242	.227	.595	6.64	3.46	.050	2.7	4.1
1.65	.172	.410	.909	.228	.260	.560	6.13	3.22	.046	2.6	4.4
1.87	.164	.386	.861	.218	.245	.535	5.82	3.06	.044	2.6	4.8
2.09	.161	.369	.826	.207	.235	.507	5.57	3.00	.042	2.8	5.1

	a	Z	Z/a	$Z+a$	$L/2$	Θ	$\frac{a^2}{2(Z+t_c)}$
CASE B	3.71	15.0	4.05	18.71	3.71	11.5	.38
CASE C	1.91	16.8	8.8	18.71	3.71	11.6	.101

TABLE 3

(Geometric and Numerical Data for Nuclear Shielding Calculations)

	Energy	M	$\frac{\mu_c t_c}{M}$	$\mu_c t_c$	t_c	$\sum \mu_i t_i$	$Z+t_c$	$F(\theta, \sum \mu_i t_i)$	C	Dose Rate (Rad/hr)
CASE B	.55	.81	1.27	1.03	3.5	20	18.5	-- --	-- --	--
	.77	.75	1.12	.84	3.4	13.6	18.4	2.2×10^{-7}	6.97×10^{-4}	.0023
	.99	.70	.95	.665	3.1	10.2	18.1	7.0×10^{-6}	2.83×10^{-4}	.0362
	1.21	.68	.93	.63	3.1	8.9	18.1	2.2×10^{-5}	1.07×10^{-4}	.0475
	1.43	.60	.93	.56	3.0	8.2	18.0	5.0×10^{-5}	3.75×10^{-5}	.0398
	1.65	.58	.94	.55	3.2	7.4	18.2	1.0×10^{-4}	1.27×10^{-5}	.0278
	1.87	.55	.95	.52	3.2	7.1	18.2	1.5×10^{-4}	3.54×10^{-6}	.0126
	2.09	.54	.96	.52	3.3	6.7	18.3	2.5×10^{-4}	7.60×10^{-7}	.0052
									TOTAL DOSE RATE	.1714
CASE C	.55	.70	.51	.36	1.2	19.9	18.0	-- --	-- --	--
	.77	.68	.50	.34	1.4	13.1	18.2	3.5×10^{-7}	6.97×10^{-4}	.00097
	.99	.59	.45	.268	1.2	9.8	18.0	8.0×10^{-6}	2.83×10^{-4}	.01090
	1.21	.55	.43	.236	1.2	8.5	18.0	3.3×10^{-5}	1.07×10^{-4}	.01830
	1.43	.52	.44	.23	1.2	7.8	18.0	7.0×10^{-5}	3.75×10^{-5}	.01480
	1.65	.51	.48	.25	1.4	7.1	18.2	1.5×10^{-4}	1.27×10^{-5}	.01100
	1.87	.50	.50	.25	1.5	6.9	18.3	1.7×10^{-4}	3.54×10^{-6}	.00382
	2.09	.49	.51	.25	1.5	6.5	18.3	2.6×10^{-4}	7.60×10^{-7}	.00140
									TOTAL DOSE RATE	.06119

TABLE 4

(Sample Calculations of Nuclear Radiation Dose Rate)

From the superposition of dose rates, the dose rate due to A equals the dose rate due to B minus that due to C. Thus the dose rate in Rad/hr is .1714-.06119 = .102. This is then converted into Rem/hr for the dose rate to be given in MR/hr (134 MR/hr). Note that 1.31 Rem equals 1 Rad.

APPENDIX B

HEAT LOSS DERIVATION

The solution to the heat transfer equation for the annular cylinder both with and without internal heat generation is given on the following page [2]. Using these solutions when considering the geometry shown in figure 5, there can be derived six equations with six unknowns. The solution of these six equations results in the calculation of $\left(\frac{Q}{\ell}\right)_{out}$. The six equations are:

$$\left(\frac{Q}{\ell}\right)_{in} = 2\pi k_c \frac{(T_1 - T_2)}{\ln(r_2/r_1)} \tag{1}$$

$$\left(\frac{Q}{\ell}\right)_{in} = \dot{Q}\pi r_2^2 - C_1' 2\pi k_f \tag{2}$$

$$\left(\frac{Q}{\ell}\right)_{out} = \dot{Q}\pi r_3^2 - C_1' 2\pi k_f \tag{3}$$

$$\left(\frac{Q}{\ell}\right)_{out} = 2\pi k_c \frac{(T_3 - T_4)}{\ln(r_4/r_3)} \tag{4}$$

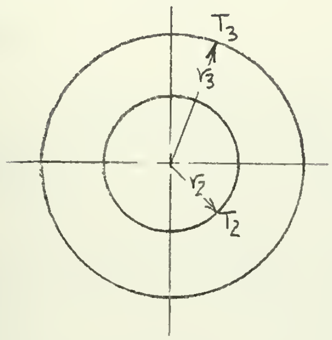
$$\left(\frac{Q}{\ell}\right)_{out} = 2\pi k_s \frac{(T_4 - T_5)}{\ln(r_5/r_4)} \tag{5}$$

$$\left(\frac{Q}{\ell}\right)_{out} = 2\pi k_I \frac{(T_5 - T_6)}{\ln(r_6/r_5)} \tag{6}$$

The known values of k and r are then substituted to simplify the six equations.

$$\left(\frac{Q}{\ell}\right)_{in} = 155\,(T_1 - T_2) \tag{1'}$$

Annulus with no Internal Heat Generation

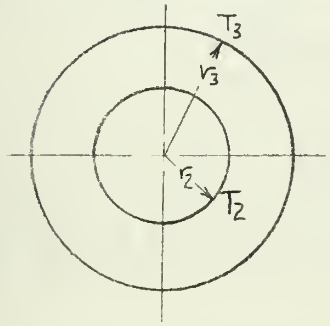


k = thermal conductivity

$$T = T_2 + \frac{T_3 - T_2}{\ln(r_3/r_2)} \ln(r/r_2)$$

$$\frac{Q}{\ell} = 2\pi k \frac{(T_2 - T_3)}{\ln(r_3/r_2)}$$

Annulus with Internal Heat Generation



$\dot{Q}$ = internal heat $\left(\frac{\text{watts}}{\text{cm}^3}\right)$

k = thermal conductivity

$$T = -\frac{\dot{Q}r^2}{4k} + C_1' \ln r + C_2'$$

$$\frac{Q}{\ell} = -2\pi k r\left[\frac{C_1'}{r} - \frac{\dot{Q}r}{2k}\right]$$

where $$C_1' = T_3 - T_2 + \frac{\dot{Q}}{4k}(r_3^2 - r_2^2)$$

$$C_2' = T_3 + \frac{\dot{Q}r_3^2}{4k} - C_1' \ln r_3$$

$$\left(\frac{Q}{\ell}\right)_{in} = \dot{Q}\,(.01225) - 20.1\,C_1' \tag{2'}$$

$$\left(\frac{Q}{\ell}\right)_{out} = \dot{Q}\,\pi\, r_3^2 - 20.1\,C_1' \tag{3'}$$

$$\left(\frac{Q}{\ell}\right)_{out} = 62.8\,(T_3 - T_4)\,\ln(r_3/r_4) \tag{4'}$$

$$\left(\frac{Q}{\ell}\right)_{out} = 119\,(T_4 - T_5)\,\ln(r_4/r_5) \tag{5'}$$

$$\left(\frac{Q}{\ell}\right)_{out} = .00502\,(T_5 - T_6)\,\ln(r_5/r_6) \tag{6'}$$

The resulting six equations are then solved simultaneously. First set the two equations for $\left(\frac{Q}{\ell}\right)_{in}$ equal to one another.

$$\left(\frac{Q}{\ell}\right)_{in} = 155\,(T_1 - T_2) = .01225\,\dot{Q} - 20.1\,C_1'$$

Then put in the value of C_1' and solve for T_2 in terms of T_3 and T_1.

$$T_2 = \frac{C_2 T_3 + 155\,T_1 + C_3}{155 + C_2} \tag{7'}$$

where $C_2 = 20.1\,\ln(.75/r_3)$

$$C_3 = \dot{Q}\left[\frac{C_2}{12.8}\,(r_3^2 - r_2^2) - .01225\right]$$

Next solve for T_3 in terms of $\left(\frac{Q}{\ell}\right)_{out}$ and T_6 by using equations 4', 5', and 6'.

$$T_3 = T_6 + C_1 \left(\frac{Q}{\ell}\right)_{out} \qquad (8')$$

where $$C_1 = \frac{\ln(r_4/r_3)}{62.8} + \frac{\ln(r_5/r_4)}{119} + \frac{\ln(r_6/r_5)}{.00502}$$

From equations 3' and 7' solve for T_3 in terms of $\left(\frac{Q}{\ell}\right)_{out}$ and T_1.

$$T_3 = T_1 - \frac{(155+C_2)\left[\left(\frac{Q}{\ell}\right)_{out} + C_5 - C_4\right] - C_2 C_3}{155\, C_2} \qquad (9')$$

where $$C_4 = \dot{Q}\pi r_3^2$$

$$C_5 = (r_3^2 - r_2^2)\frac{\dot{Q}\, C_2}{12.8}$$

Then T_3 can be eliminated between equations 8' and 9' to find $\left(\frac{Q}{\ell}\right)_{out}$ in terms of T_1, T_6, r_1, r_2, r_3, r_4, r_5, and r_6.

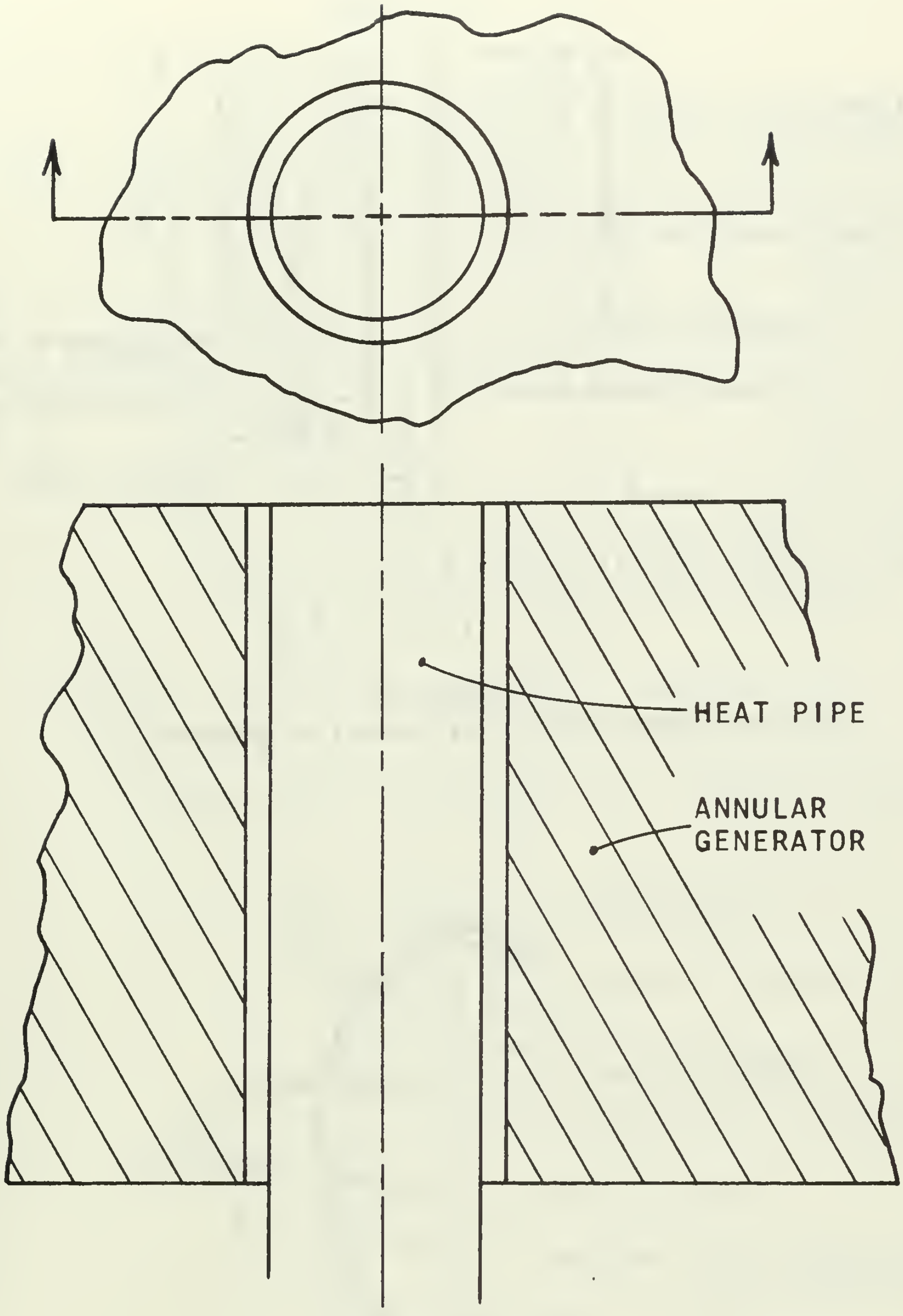
$$\left(\frac{Q}{\ell}\right)_{out} = \frac{(155+C_2)(C_4-C_5) + 155\, C_2 (T_1 - T_6) + C_2 C_3}{155\, C_1 C_2 + 155 + C_2}$$

APPENDIX C

CRITICAL DIMENSIONS AND VOLUME DERIVATIONS

Knowing the fixed outside diameter of the heat pipe (1 inch) and the required hot plate area of the generator (A-as specified in the SNAP-21 design) the length of the heat pipe needed next to the generator to fulfill the required hot plate area is easily calculated. There is an additional specification of 1/16 of an inch gap between the heat pipe and the hot plate for heat transfer by conduction and radiation (at a temperature drop of 200°F). Figure 23 shows the geometry and the required hot plate length.

From the figures 24, 25, 26 and 27 the respective volumes of the generator cold frame, pressure vessel, shield, and fuel capsule can be easily verified. Note that in each case these volumes are functions of the variable radii (RF-radius of the fuel, RS-radius of the shield, RI-radius of the insulation).

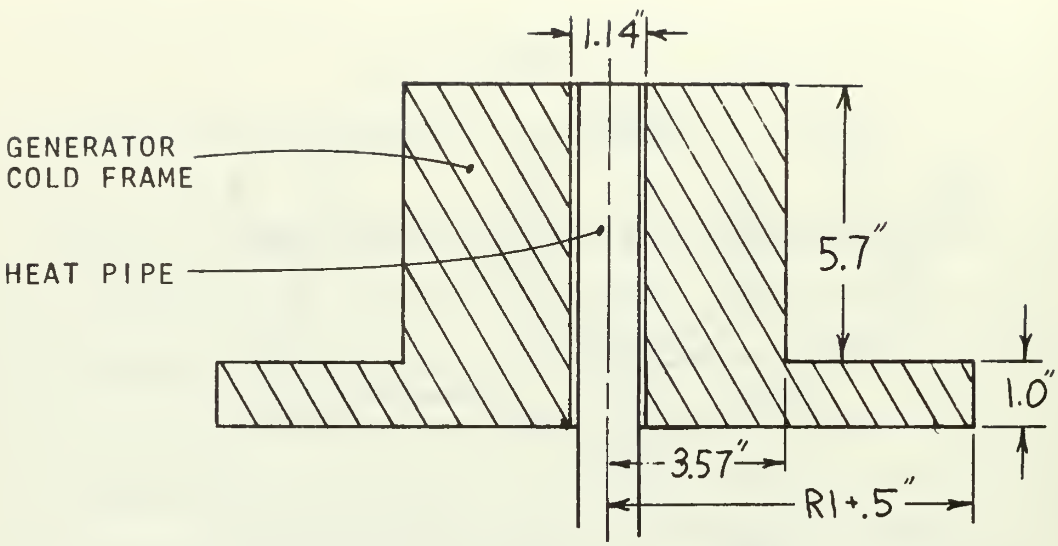


total hot plate area = $A = 6.6\ in^2$

$A = \frac{\pi}{4} D^2 L$ $\qquad\qquad D = 1\frac{1}{8}$ in

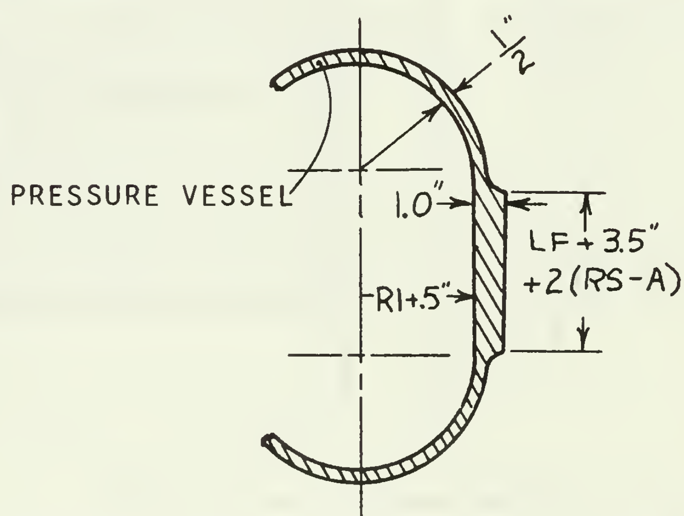
$\therefore L = 6.7$ in

Figure 23
(Length dimension of annular generator)



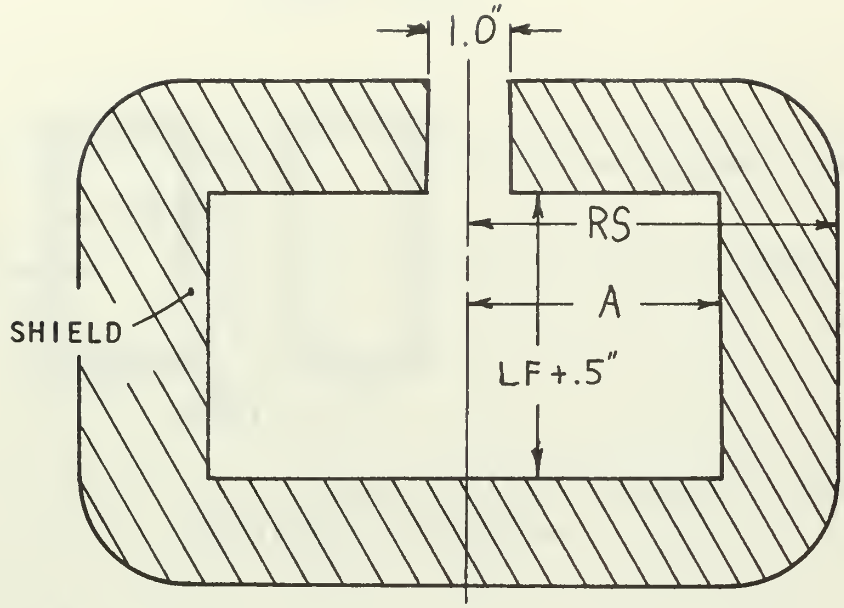
$$\text{VOLUME} = \pi\left[((3.57)^2-(.57)^2)\ 5.7 + ((RI+.5)^2-(.57)^2)\right]$$

Figure 24
(Volume derivation of annular generator)



$$\text{VOLUME} = \pi\left[((RI+1.5)^2-(RI+.5)^2)(LF+3.5+2(RS-A)) \\ (4/3)((RI+1.)^3-(RI+.5)^3)\right]$$

Figure 25
(Volume derivation of pressure vessel)



$$VOLUME = \pi\left[RS^2(LF+.5+2(RS-A))-.86A(RS-A)^2 -.25(RS-A)-A^2(LF+.5)\right]$$

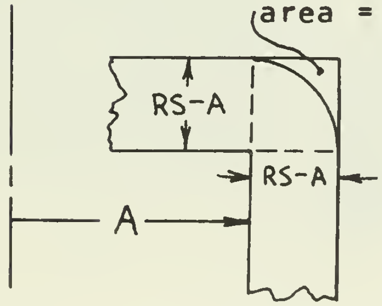
where $\pi RS^2(LF+.5+2(RS-A))$ = volume of solid cylinder

$\pi(RS-A)(1/2)^2$ = volume cut out for passage of heat pipe

$\pi A^2(LF+.5)$ = volume cut out for fuel and fuel capsule

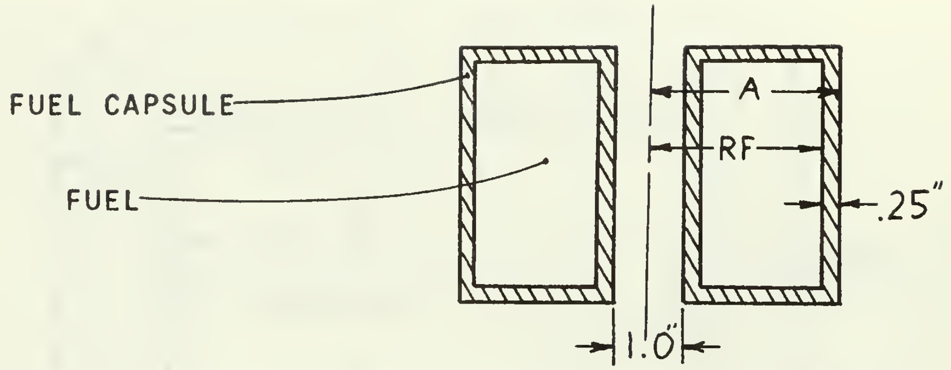
$\pi .86A(RS-A)^2$ = volume cut out for the rounded corners (i.e. see below)

$area = (1-\pi/4)(RS-A)^2$



$$\begin{aligned} volume &= 2\pi(2A)(area) \\ &= (4-\pi)\pi A(RS-A)^2 \\ &= .86A(RS-A)^2 \end{aligned}$$

Figure 26
(Volume derivation of shield)



$$\text{VOLUME} = \pi\left[.5(A^2-(.5)^2)+(A^2-RF^2)LF + ((.75)^2-(.5)^2)LF\right]$$

Figure 27
(Volume derivation of fuel capsule)

APPENDIX D

COMPUTER PROGRAM

```
C-------------------------DEFINITIONS-------------------------------------C
C                                                                         C
C          RF=RADIUS OF FUEL                                              C
C          RI=RADIUS OF INSULATION                                        C
C          RS=RADIUS OF SHIELD                                            C
C          LF=LENGTH OF FUEL                                              C
C          FUELG=THERMAL HEAT TO GENERATOR                                C
C          FUELS=THERMAL HEAT LOSS THROUGH INSULATION AND SUPPORTS        C
C          FUEL=TOTAL FUEL=FUELG+FUELS                                    C
C          DOSET=DOSE IN REM/HR AT SURFACE OF PRESSURE VESSEL             C
C          DOSE1=DOSE DUE TO CYLINDER ONE                                 C
C          DOSE2=DOSE DUE TO CYLINDER TWO                                 C
C          WEIS=WEIGHT OF SHIELD                                          C
C          WEIP=WEIGHT OF PRESSURE VESSEL                                 C
C          WEIC=WEIGHT OF FUEL CAPSULE                                    C
C          WEIG=WEIGHT OF GENERATOR AND MOUNTING PLATE                    C
C          WEIF=WEIGHT OF FUEL                                            C
C          EFF1=MATERIAL EFFICIENCY                                       C
C          EFF2=OVERALL EFFICIENCY                                        C
C                                                                         C
C-------------------------------------------------------------------------C
      REAL LF
      COMMON AA(7), AB(7), AC(7), AD(7), AF(7), AF(7), AG(7)
      READ 500 ,AA,AB,AC,AD,AE
      READ 499 ,AF,AG
      PRINT 500 ,AA,AB,AC,AD,AE
      PRINT 499 ,AF,AG
      DO 400 I=1,51
      RF=1.29+.01*I
      DO 400 II=1,260
      RS=2.99+.01*II
      RI=RS+1.2
      IF (RS-RI) 1,400,400
    1 FUELG=144.
      FUELS=56.
      CALL QGEN (RI,F)
      FUELG=F
      IF (FUELG-150.) 49,49,400
   49 FUEL=FUELS+FUELG
      LF=FUEL/(3.1416*((RF**2)-(.75**2))*13.1)
      CALL HEAT (RF,RS,RI,LF,QCT)
      IF (QCT-60.) 48,48,400
   48 IF (ABS(FUELS-QCT)-.1) 51,51,50
   50 FUELS=QCT
      GO TO 49
   51 FUELS=QCT
      FUEL=FUELS+FUELG
      LF=FUEL/(3.1416*((RF**2)-(.75**2))*13.1)
```

```
      CALL RADAT (RF,RS,RI,LF,0.0,DOSE1)
      CALL RADAT (.75,RS,RI,LF,RF-.75,DOSE2)
      DOSET=DOSE1-DOSE2
      IF (DOSET-.225) 2,2,400
    2 IF (DOSET-.175) 400,400,3
    3 EFF1=13.8/FUELG
      EFF2=10./FUEL
      A=RF+.25
      VOLS=3.14*(RS**2*(LF+.5+2.*(RS-A))-.86*A*(RS-A)**2-.25*(RS-A)
     2-A**2*(LF+.5))
      VOLC=3.14*((A**2-.75**2)*.5+(A**2-RF**2)*LF+LF*(.75**2-.5**2))
      VOLP=3.14*(((RI+1.5)**2-(RI+.5)**2)*(LF+3.5+2.*(RS-A))
     1+(4./3.)*((RI+1.)**3-(RI+.5)**3))
      VOLG=3.14*(((3.57)**2-(.57)**2)*5.7+((RI+.5)**2-(.57)**2)*1.)
      WEIS=.629*VOLS
      WEIC=.323*VOLC
      WEIP=.16*VOLP
      WEIG=.32*VOLG
      WEIF=FUEL/(.21*453.6)
      WEIT=WEIS+WEIC+WEIP+WEIG+WEIF
      PRINT 498 ,RF,RS,RI,LF,DOSE1,DOSE2,DOSET
      PRINT 497 ,FUELG,FUELS,FUEL
      PRINT 496 ,WEIS,WEIC,WEIP,WEIG,WEIF,WEIT
      PRINT 495 ,EFF1,EFF2
  400 CONTINUE
  495 FORMAT (/3X,'GENERATOR EFF =',F8.5/3X,'OVERALL EFF =',F8.5////)
  496 FORMAT (/3X,'WEIGHT OF SHIELD =',F9.2/3X,'WEIGHT OF CAPSULE =',
     1F9.2/3X,'WEIGHT OF PRESSURE VESSEL =',F9.2/3X,
     1'WEIGHT OF GENERATOR =',F9.2/3X,'WEIGHT OF FUEL =',
     1F9.2/3X,'TOTAL WEIGHT =',F9.2)
  497 FORMAT (3X,'HEAT TO GENERATOR =',F9.3/3X,'HEAT LOSS =',F9.3/
     13X,'TOTAL FUEL = HEAT TO GENERATOR + HEAT LOSS =',F9.3)
  498 FORMAT (3X,'FUEL RADIUS =',F8.3/3X,'SHIELD RADIUS =',F8.3/3X,
     1'INSULATION RADIUS =',F8.3/3X,'FUEL LENGTH =',F8.3//3X,'DOSE1 =',
     1F9.3,'     DOSE2 =',F9.3/3X,'DOSET=DOSE1-DOSE2=',F9.3/)
  499 FORMAT (7E11.3)
  500 FORMAT (7F7.3)
      STOP
      END
```

```
      SUBROUTINE QGEN (R,FUE)
C-------------------------DEFINITIONS-----------------------------------C
C                                                                       C
C           RC = OUTER RADIUS OF INSULATION INCLUDING STRUCTURAL MATERIALC
C           TC = TEMPERATURE AT COLD END OF THERMOCOUPLE                C
C           FUE = TOTAL HEAT TO THERMOELECTRIC GENERATOR                C
C                                                                       C
C-----------------------------------------------------------------------C
      RO=R+.5
      TO=570.
      FUE=144.
    3 T1=(ALOG(RC/1.3))*((12.*3.41)/(6.28*209.*1.))*(FUE-13.8)+505.
      Q=((1560.-TC)/(1560.-T1))*FUE
      IF (Q-150.) 4,4,1
    4 IF (ABS(FUE-Q)-.1)1,1,2
    2 FUE=Q
      TO=T1
      GO TO 3
    1 FUE=Q
      RETURN
      END


      SUBROUTINE HEAT (RFF,RSS,RII,LFF,QCUTT)
C-------------------------DEFINITIONS-----------------------------------C
C                                                                       C
C           RII = RADIUS OF INSULATION                                  C
C           RSS = RADIUS OF SHIELD                                      C
C           RFF = RADIUS OF FUEL                                        C
C           LFF = LENGTH OF FUEL                                        C
C           T1 = HEAT PIPE TEMPERATURE                                  C
C           QDOT = SPECIFIC POWER OF THE FUEL                           C
C           QCUT = HEAT LOSS THROUGH THE INSULATION                     C
C           QCUTT = TOTAL HEAT LOSS                                     C
C                                                                       C
C-----------------------------------------------------------------------C
      T1=1300.
      T6=45.
      REAL LFF
      QDOT=77100.
      QOUT=0.0
      C1=(ALOG((RFF+.25)/RFF))/62.8+(ALOG(RSS/(RFF+.25)))/119.
     2+(ALOG(RII/RSS))/.00502
      C2=20.1/(ALOG(RFF/.75))
      C3=QDOT*(-.01225+(C2/12.8)*((RFF/12.)**2-.0039))
      C4=QDOT*((RFF/12.)**2)*3.1416
```

```
      C5=C3+QDCT*.01225
      QOUT=(((155.+C2)*(C4-C5)+(T1-T6)*(155.*C2)+C2*C3)/
     3(155.*C1*C2+155.+C2))*((LFF+RFF)/(12.*3.41))
      QOUTT=QOUT+7.+40.
      RETURN
      END


      SUBROUTINE RADAT (FR,SR,IR,FL,Q,DOSE)
C-----------------------DEFINITIONS----------------------------------C
C                                                                    C
C            FR = RADIUS OF FUEL                                     C
C            IR = RADIUS OF INSULATION                               C
C            SR = RADIUS OF SHIELD                                   C
C            FL = LENGTH OF THE FUEL                                 C
C            DOSE = DOSE AT THE SURFACE OF THE PRESSURE VESSEL       C
C                                                                    C
C--------------------------------------------------------------------C
      COMMON UC(7), UH(7), UU(7), UX(7), B(7), K(7), C(7)
      REAL IR,M,MM,K
      DOSE=0.0
      Z=2.54*(IR+.5+.97-FR)
      X=Z/(2.54*FR)
      DO 400 L=1,7
      UT=2.54*(UU(L)*(SR-FR-.25-Q)+UX(L)*.97+UH(L)*.25)
      W=UC(L)*(Z+2.54*FR)
      IF (W-6.) 2,1,1
    1 M=1.05-.03*X
      GO TO 100
    2 IF (W-5.) 4,3,3
    3 M=.95+(W-5.)*.1-.03*X
      GO TO 100
    4 IF (W-4.) 6,5,5
    5 M=.82+(W-4.)*.13-.03*X
      GO TO 100
    6 IF (W-3.5) 8,7,7
    7 M=.74+((W-3.5)/.5)*.08-X*(.025+.01*(W-3.5))
      GO TO 100
    8 IF (W-3.) 10,9,9
    9 M=.62+((W-3.)/.5)*.12-X*(.02+.01*(W-3.))
      GO TO 100
   10 M=.62+((W-3.)/.5)*.12-.02*X
  100 IF (X-2.) 11,11,12
   11 MM=1.23+.02*UT
      GO TO 200
   12 IF (X-4.) 13,13,14
```

```
 13 MM=1.23+((2.-X)/2.)*.37+UT*(.020+.005*((2.-X)/2.))
    GO TO 200
 14 IF (X-6.) 15,15,16
 15 MM=.86+((4.-X)/2.)*.14+UT*(.015+.002*((4.-X)/2.))
    GO TO 200
 16 IF (X-8.) 17,17,18
 17 MM=.72+((6.-X)/2.)*.17+.013*UT
    GO TO 200
 18 MM=.55+((8.-X)/2.)*.05
200 UTT=UT+M*MM
    TC=M*MM/UC(L)
    ANT=(FL*2.54)/(2.*(Z+TC))
    IF (ANT-.342) 20,19,19
 19 F=(.253*EXP(-UTT))*(ANT/.342)
    GO TO 300
 20 IF (ANT-.258) 22,21,21
 21 F=(EXP(-UTT))*(.22+((ANT-.258)/.84)*.033)
    GO TO 300
 22 F=(EXP(-UTT))*(.165+((ANT-.174)/.84)*.055)
300 G=((FR*2.54)**2)/(2.*(Z+TC))
    DOS=K(L)*B(L)*C(L)*G*F*(.8*33./.21)*(3.7E+10)/.83
    DOSE=DOS+DOSE
400 CONTINUE
    RETURN
    END
```

BIBLIOGRAPHY

1. Angrist, Stanley W., Direct Energy Conversion, Allyn and Bacon, Inc., Boston, 1965.

2. Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, Oxford University Press, Great Britain, 1959.

3. Chapman, Alan J., Heat Transfer, Macmillan Company, New York, 1967.

4. Cheung, Henry, A Critical Review of Heat Pipe Theory and Applications, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-50453, 1968.

5. Corliss, William R. and Harvey, Douglas G., Radioisotopic Power Generation, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1964.

6. Etherington, Harold, Editor, Nuclear Engineering Handbook, McGraw-Hill Book Company, Inc., New York, N. Y., 1958.

7. Feldman, K. Thomas, Jr., and Whiting, Glen H., "The Heat Pipe", Mechanical Engineering, February, 1967.

8. Feldman, K. Thomas, Jr., and Whiting, Glen H., "Applications of the Heat Pipe", Mechanical Engineering, November, 1968.

9. Levy, E. K., "Theoretical Investigation of Heat Pipes Operating at Low Vapor Pressures," Transactions of the ASME, November, 1968.

10. Martin Nuclear Division Report #MND-322-25, SNAP-21A Ten-Watt Deep Sea Isotopic Power Supply, Summary Report Phase 1, 1965.

11. Rockwell, Theodore III, Ed., Reactor Shielding Design Manual, D. Van Nostrand Company, Inc., Princeton, New Jersey.

12. 3-M Company Report # MMM(3321)-19, SNAP 21-B Program, Deep Sea Radioisotope-fueled Thermoelectric Generator Power Supply System, Final Report, June 1966.

13. 3-M Company Report # MMM(3691)-49, SNAP-21 Program, Phase II, Final System Safety Analysis, June 1969.

14. Ward, James J. and Blair, Larry S., Parametric Analysis of Radioisotope Fueled Thermionic Generators, Lewis Research Center, Cleveland, Ohio.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	20
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Naval Ship Systems Command Code 2052 Department of the Navy Washington, D. C. 20360	1
4.	Mechanical Engineering Department Naval Postgraduate School Monterey, California 93940	2
5.	Professor P. J. Marto Mechanical Engineering Department Naval Postgraduate School Monterey, California 93940	1
6.	Professor P. F. Pucci Mechanical Engineering Department Naval Postgraduate School Monterey, California 93940	1
7.	LTJG Benjamin J. Ewers, Jr., USN 1947 Blaine Ave., Racine, Wisconsin 53405	2
8.	Mr. Robert Pannemann Defense Products Department Bldg 551 3-M Company St Paul, Minn. 55101	1

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
A Parametric Analysis of a Deep Sea Radioisotopic Thermoelectric Generator Employing a Heat Pipe

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Master's Thesis; June 1969

5. AUTHOR(S) (First name, middle initial, last name)
Benjamin James Ewers, Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1969	69	14

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

13. ABSTRACT

A parametric design analysis was performed using a heat pipe in an existing deep sea Radioisotopic Thermoelectric Generator (SNAP-21). Heat is transferred from an annular fuel pellet to an annular thermoelectric generator through a connecting heat pipe. The fuel pellet is fully shielded so that the thermoelectric generator is easily removable. Overall efficiency and the weight of major components were determined for varying fuel radii of from 1.3 to 1.7 inches and for varying insulation thicknesses of from 1.0 inch to 2.0 inch.

The analysis indicates that there is a particular fuel radius (at constant insulation thickness) at which minimum weight is reached, while the maximum overall efficiency is obtained at a larger fuel radius. The median design has an overall efficiency (at the beginning of life) of 5.4% and a total weight of 570 lbs. These design results, when compared to the existing SNAP-21 design gives an increase in overall efficiency of at least 7%, and a reduction in total weight of 12%.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radioisotopic Thermoelectric Generator						
Heat Pipe						
SNAP-21						